Shark Fishing in the Indian Seas: A Quantitative Risk Assessment of the Impacts of Longline Fishing on the Sustainability of Regional Shark Populations

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Shark Fishing in the Indian Seas: A Quantitative Risk Assessment of the Impacts of Longline Fishing on the Sustainability of Regional Shark Populations

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Abstract

This project endeavored to provide a formative, contemporaneously applicable, and fully quantitative baseline of a significant component of the shark harvest produced by the nation of India, namely, the longline bycatch mortality for sharks generated from the commercial-scale fishing activity in the extensive oceanic region of India's Exclusive Economic Zone (EEZ), the nature and scope of which is little understood.

Worldwide, shark populations have experienced marked declines due to the advent of modern industrial fishing. Additionally, the life-history and reproductive characteristics of these species, which include longer lifespans, slower growth, fewer offspring, and generally reduced fecundity, constrain group level reproduction and replacement rate compared to that of many commercially targeted and managed teleosts.

Although generally true at a global level, shark population depletion has varied in nature and/or rate around the world, with significant unknowns persisting in relation to the waters and seas surrounding developing and recently developed economies; in many cases these waters have not been subject to comparable levels of oversight, active management, and/or assessment as those found in other more established global fisheries.

India, over the last decade and a half approximately, has been positioned as the second largest contributor to the global shark harvest in terms of overall tonnage which in turn raises the following question: Is this country mirroring similar global trends of shark population decline due to its fishing activity? Addressing this question in a formatively useful way defines the focal pursuit of this research venture.

A relevant, significant, though sparsely assessed source of shark fishing mortality experienced within the broader Indian EEZ—non-target bycatch of sharks, specifically that which is generated from the oceanic longline (LL) fishery—was ultimately analyzed to address the primary hypothesis: Although only one among many marine sub-fisheries, the unassessed status of the oceanic LL fishery presently obscures a reality of unsustainable harvest, such that the community of shark species/stocks extant within the oceanic sector of the Indian EEZ are incurring unsustainable levels of fishing mortality (F) through bycatch in longline gear.

To examine the impacts of longline fishing on shark populations in the Indian EEZ, this study utilized advanced statistical methods that focus on the rapid assessment of data limited stocks. In particular, a data-limited status assessment methodology devised by Shijie Zhou and various colleagues—known as the Sustainability Assessment for Fishing Effects (SAFE) method—and Bayesian Hierarchical Analysis were applied. The use of the former afforded a tractable method for longline bycatch mortality estimation (F) through the relationship among target species mortality, a number of bycatch species' catchability parameters, and spatial overlap of fleet fishing effort with bycatch species habitat. Key outputs were defined as parameters or logical functions thereof within said Bayesian hierarchal models and mean posterior estimates were derived.

Two separate Bayesian Models where constructed and run using the OpenBUGS statistical software (3.2.2, OpenBUGS Foundation, UK). The first was designed to derive a marginal posterior distribution of fishing mortality (F), and the second was used to produce marginal posterior distributions of the following biological reference points:

F_{msm}, F_{lim}, and F_{crash}. F_{msm} equals the instantaneous fishing mortality rate that corresponds to the maximum number of fish in the population that can be killed by fishing in the long term; F_{lim} equals instantaneous fishing mortality rate that corresponds to the limit biomass B_{lim}, where B_{lim} is assumed to be half of the biomass that supports a maximum sustainable fishing mortality ($0.5B_{msm}$); F_{crash} equals minimum unsustainable instantaneous fishing mortality rate that, in theory, will lead to population extinction in the long term.

These reference points were derived via integration with respect to the specific parameter across all model-defined upstream conditional dependencies; the relationships where showcased in formal terms using a series of Directed Acyclic Graphs (DAG) and a defined graphical lexicon. The evaluation of integrals was accomplished via large iteration Monte Carlo Markov Chain simulation using a Gibbs sampling algorithm within the OpenBUGS software suite. Mean values (estimates) of corresponding marginal posteriors as well as their credible intervals acquired via simulation were equivalent to point values for the otherwise unknown parameters of interest. Once acquired, these values were then elevated for usage in a final, species-specific status determination based on a straight forward value relationship, specifically between Instantaneous Fishing Mortality (F) and a corresponding set of biological reference points (F_{msm}, F_{lim}, F_{crash}).

The relationships and corresponding species status determinations were garnered using the Credible Interval ($C_R I$), which is the Bayesian analogue to the frequentist Confidence Interval, as follows: $F < F_{msm}$, = Low-Risk (L; i.e. sustainable mortality); $F \geq \min[F_{msm}]$ *or* $F + 95\%\ C_R I \geq F_{msm}$, = Precautionary medium risk (m); $F_{msm} \leq F < F_{lim}$,= Medium risk (M); $F \geq \min[F_{lim}]$ *or* $F + 95\%\ C_R I \geq F_{lim}$, = Precautionary high risk (h); F_{lim}

$\leq F < F_{crash}$, = High risk (H); $F \geq \min[F_{crash}]$ *or* F +95% $C_{R}I \geq F_{crash}$, = Precautionary extreme high risk (e); and $F \geq F_{crash}$, = Extreme high risk (E). F_{crash} is the level at which minimum, unsustainable fishing mortality has been achieved, which, when maintained over the long-run, results in local/population extinction. Values in still greater excess thereof further intensify the rate of depletion towards that eventuality.

Spanning the time period 2010-2014, both for individual years and as a grand mean thereof, Fishing mortality (F) estimates (posterior given as: $\hat{\mu}_{\mathrm{F}}^{\omega}$) were generated for (30) species of sharks, all of which, either exclusively or in part, are known to inhabit the oceanic ecosystem of the Indian EEZ. Biological reference points F_{msm}, F_{lim}, F_{crash} (posteriors: $\theta_{\mathrm{Fmsm}}, \theta_{\mathrm{Flim}}, \theta_{\mathrm{Fcrash}}$) were produced for 17 (of 30) species. Additionally, point values for other relevant parameters were derived (e.g. natural mortality [M]) for 17 species (posterior: θ_{M}), some of which are new within the scientific literature (specifically the Longfin Mako (*Isurus paucus*) and possibly the Gulper Shark (*Centrophorus granulosus* for the Indian Ocean Stock). Others include the mean, year-wise longline yellowfin tuna (YFT; *Thunnus albacares*) catch (C) within the Indian Oceanic EEZ, and the average area of longline fishing impact within the Indian Oceanic EEZ (posterior: $\mu_{Aif_0}^{\varepsilon}$). The fishing mortality values derived in this study may likely be the first values in the literature for many of the species evaluated, at least in the context of the Indian Ocean and certainly for the India EEZ. Of the 17 shark species for which both F and corresponding biological reference points (F_{msm}, F_{lim}, F_{crash}) were derived, one species was defined as Low Risk, one as Precautionary Medium Risk, three as Precautionary High Risk, one as High Risk, two as Precautionary Extreme High Risk, and nine species as Extreme High Risk. Many of the species represented in the higher risk categories are currently subjected to trade control and general protection under both the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Convention on Migratory Species Protection Agreement (CMS); India is a ratified member Party to both conventions and thus is theoretically obliged to respect/implement necessary control actions.

Dedication

To my loving family, both present and departed. To my friends, those joyful shepherds of spirit. To my mentors, both inspired and sage. To India, Bhārata, the southern petal in the shade of Meru. To fisherman, sailors of ships, and all those who venture on unsteady seas. To the future, may it be gilded with the fruits of our enduring efforts, known and unknown, great and small.

इति ते ज्ञानमाख्यातं गुह्याद्गुह्यतरं मया।
विमृश्यैतदशेषेण यथेच्छसि तथा कुरु।।१८-६३।।

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Acknowledgements

Many generous and brilliant actors where integral in the conceptualization and execution of this research project: some explicitly, some as keystone educators and scholars involved in my journey through higher education thus far, others who helped foster professional development in life sciences and sustainability studies during my time as a graduate student, and some just inspired mentors in erudition and the wisdom of living. There are far too many names to list with any semblance of adequacy, and therefore I extend the full breadth of my gratitude to all those named and many unnamed.

Firstly, I would like to thank Dr. Gregory Skomal for his discipline-leading expertise, generosity of time and intellect, and seemingly inexhaustible patience in acting as my Thesis Director; I am so very grateful, and I hope you will take pride in what I have accomplished as a pupil. Next, I would like to thank Dr. Mark Leighton, in both capacities as an exceptional professor in the Sustainability & Environmental Management program and as my Research Advisor; your wisdom, organization, and perennial belief in this project have meant more than you know. I would like to thank George Buckley for his willingness to act as a facilitator when this project was no more than a scholarly dream, as well as for his exuberance in bearing the torch for sustainability and marine studies within the SEM faculty. I would like to thank Dr. Ramon Sanchez for his determination to let no idea be too big and his wisdom in letting his students rise to the occasion, even if it was.

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I would like to thank Dr. Daniel Janzen, a longtime inspiration, mentor, model scientist, and advocate for life and its unending diversity. Moreover, I would like to thank the University of Pennsylvania Faculty of Biology as well as the many excellent teachers and mentors of Marist School; I am truly reaping what you have sown.

Lastly, this venture was seeded by a profound reverence, thirst for understanding, and in general the undeniable magnetism of place that is South Asia and India in particular. Emergent "from the navel of the world," this vast land and its peoples represent a fixture so grand and pressing that the author can only hope to honor it with the tool of scholarship. Such a vantage, and by necessity the formative circumscription thereof, was truly the gift of the combined wisdom of a number of great scholars of South Asia under which I been privileged to study. In this respect, I must sincerely thank Dr. Deven Patel, Dr. Diana Eck, Dr. Michael Meister and Dr. Sunil Amrith for both their knowledge and inspiration.

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Chapter I

Introduction

Chondrichthyans (Figure 1) comprise one of the oldest and most ecologically diverse vertebrate lineages: arising at least 420 million years ago and rapidly radiating out to occupy the upper tiers of aquatic food webs (Compagno, 1990; Kriwet, Witzmann, Klug, & Heidtke, 2008). Today, this group is one of the most diverse lineages of predators on earth and exhibit significant functional roles in the top-down control of coastal and oceanic ecosystem structure and function alike (Ferretti, Worm, Britten, Heithaus & Lotze, 2010; Heithaus, Wirsing, & Dill, 2012).

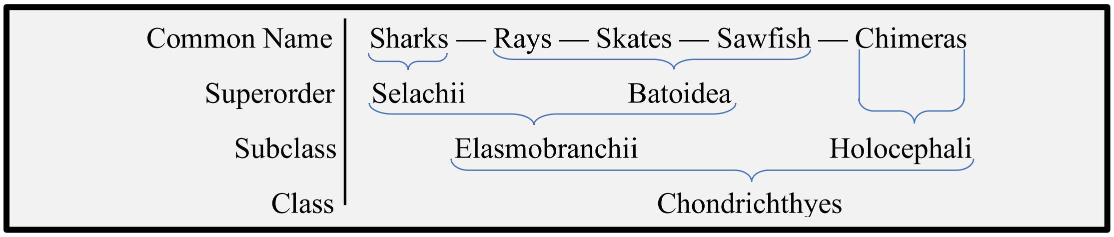


Figure 1. Group-level taxa and nomenclature.

At a group level, sharks are subject to biologically accentuated fragility to fishing pressures due to specific life-history characteristics which imbue inherent vulnerabilities, including longer lifespans, slower growth, and fewer offspring, whose generally depressed replacement capacities are further aggravated by the modern commercial paradigm of increased fishing effort (Cortés, 2000; García, Lucifora, & Myers, 2008; Dulvy & Forrest, 2010; Musick, 1999), especially in pursuit of more productive target teleosts (Stevens, Walker, Cook, & Fordhan, 2005). Due to this reality, the background demographic character of the majority of observed stark stocks globally is defined by pervasive declination trends (Worm et al., 2013).

In the modern era, a confluence of contemporaneously antagonistic factors is working against the long-term, group-level survival of sharks, and more generally Chondrichthyes (sharks, rays, skates, sawfish & chimeras [Camhi, Fowler, Musick, Bräutigam, & Fordham, 1998]) (Figure 1). Indicator factors which signal exacerbation of such inherent vulnerabilities of sharks and/or general lack of knowledge about the nature of shark landings in a fishery may help communicate the probability of experienced risk where it otherwise may be unknown or unassessed and in turn prioritize future conservation efforts and needed scientific assessment via a variety of frameworks (e.g. Hobday et al., 2011). Even within the context of a semi-rigorous or ad hoc modality of consideration, the presence and intensity of various of these indicator factors evinced simultaneously, in addition to significant knowledge gaps as to the true on-ground status of potentially affected shark stocks, is deemed significant enough to elevate the regional seas of India as a priority domain of research interest.

Over the last 15 years, the nation of India has been the second largest global harvester of sharks, accounting for roughly 8.9% of annual global shark landings by gross tonnage according to self-reported landings (Lack & Sant, 2009; Lack & Sant, 2011; Dent & Clarke, 2015; FAO, 2018), positioned behind only Indonesia regarding highest national contribution (Dent & Clarke, 2015) (Figure 2). Given the prominence of India as a leading contributor nation in the contemporary global shark harvest and history of incomplete /questionable data reporting as well as the high prevalence of finning in the

Indian Ocean (Smale, 2008), and India specifically (Hausfather, 2012; Dhaneesh & Zacharia, 2013), these declines could even far outstrip background averages.

Figure 2. Shark cart (photo by author, Chennai. 2016).

Bhathal (2014) cites the current Indian vessel capacity in the coastal zone to be approximately three times higher than optimum capacity; it may be hypothesized that the Indian regional seas are experiencing at least similar trends to status quo global stock declines for sharks.

Additionally, the territory of the Indian EEZ is couched directly in, or at least located in the immediate periphery of, a known shark fishing “threat hotspot” of uncertain regulation. Dulvy et al. (2014) identifies the FAO Regions of the Eastern (57) and Western Indian Ocean (51) (Figure 3) as the number 1 and 4 highest priority regions respectively in terms of needed scientific and conservation focus (out of 19 FAO regions). The rankings were determined via a proprietary analysis accounting for proportion of threatened taxa within the regional Chondrichthyan community, regional species knowledge-gaps, and regional endemicity; the southern tip of India designates the meridian between these two FAO regions and is thus assumed to be at the crossroads of those regional realities, and likely to a non-trivial degree (Figure 3).

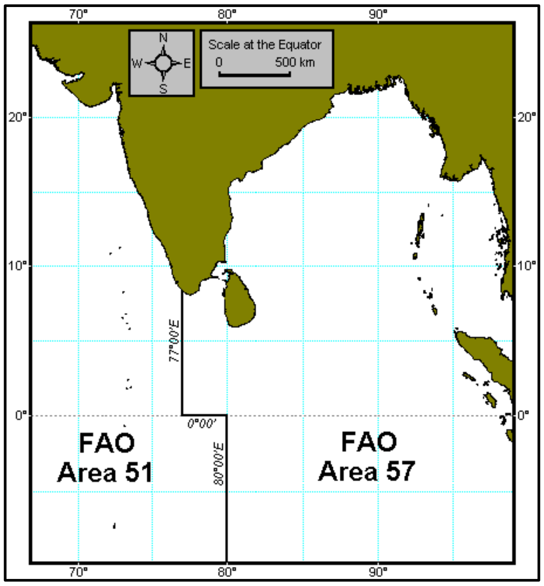


Figure 3. Map of India in relation to FAO regions in the North Indian Ocean. FAO Region 51 and 57 expand significantly beyond the map.

In a recent follow-up study, Dulvy et al. (2017) ranks India as the number 1 country with the greatest need for shark and ray conservation and fisheries management improvements using composite index of FAO landings, shark fin trade, priority fisheries species and uncertainty in species differentiation of catch, broadly confirming the latter assumption.

Yet, even as global awareness on the subject of ocean-basin level elasmobranch depletion has increased in recent years (Simpfendorfer, Heupel, White, & Dulvy, 2011), and despite India's substantial national contribution to the global harvest, priority geography, and stressed regulatory architecture, the nation itself (as well as its general regional cluster) has received limited scientific attention at an international level (Jadhav, 2012) in a manner commensurate with its various "warning" characteristics. Although there exists a modest though active cohort of participants specializing in the investigation of regional sharks' biology, ecology and interaction with proximate fisheries (Akhilesh, 2014), in addition to numerous centers and institutes with varied (albeit with sometimes overlapping and other times tangential) mandates in ocean research, key, system-level gaps in macro data-collection design for long-form assessment of said stocks leave such actors with incomplete tool-sets with which to evaluate such critical stock phenomena, such as population response to fishing mortality.

Major programmatic deficiencies in the immediate and long-term effective comprehension of true status of regional sharks include the following features: 1) the lack of species specific partitioning among the "Shark, rays and skates" aggregate reporting category in Indian National catch reports by the Central Marine Fisheries Research Institute [of India] (CMFRI) (Musick & Musick, 2011); 2) the use of site aggregation from commercial landing centers essentially exclusively, as well as gear type, as proxies for true point-of-catch information, geographically speaking (Srinath, Kuriakose, & Mini, 2005; Mini, 2015; c.f. Espinoza-Tenorio, Espejel, Wolff, & Zepeda-Dominquez, 2011; Jadav, 2012; Chrysafi, & Kuparinen, 2016); 3) and finally, the lack of long-term (or in-perpetuity) monitoring projects to obtain fisheries independent data-streams for shark mortality by gear, together define the major, tripartite structural shortcomings to the furnishing of adequate status assessments for sharks under the current analytical program. Additionally, the common practice of institutional sequestration of raw data, often de jure unavailable to the public without extraordinary permission, generally stymies external efforts to engage an otherwise significant well of regional data as well as prevents potentially innovative meta-analysis (Jadhav, 2012). Without the general communication of a rationale for needed confidentiality for some of these datasets, the practice could be conceived as broadly antagonistic to the Code of Conduct for Responsible Fisheries (§7.4; Anon, 1995). Most of these conditions are simply a byproduct of the regional character and complications of the fishery, which is extremely large and highly populated, as well as capacity/budgetary constraints. Although understandable, overcoming these deficiencies should remain a focal goal should effective conservation of this class of organisms be realized. Furthermore, the prevalence of IUU fishing in the region (which appears to be in decline, though still common; Pramod, 2012) in addition to the consideration of the claim that reported FAO data (the same as national data) may only represent between 25-33% of true catch (Clarke et al., 2006; Worm et al., 2013), provides additional obfuscation. In short, despite numerous, plausibly external signals as to the reality beneath the waves, various confounding factors to stock comprehension still reign, to the extent that the following question still requires a formative and quantitatively vouchsafed answer: Is the country with the second highest global shark catch mirroring similar global trends of decline (Worm et al., 2013) due to its marine fishing activity?

It is generally believed that data-constraints have resulted in the slow aggregation of knowledge and stymied the effective study of shark population resilience (or lack thereof) to fishing effort within India's regional seas, even up to the present (Musick & Musick, 2011). Although still operative, a relevant sub-sector of shark fishing mortality within the broader Indian EEZ was ultimately identified as available to analysis and as such hypothetically address the range of outcomes previously described. This sub-sector was the oceanic longline fishery, and specifically shark bycatch mortality generated therefrom.

Research Significance and Objectives

In the context of 1) pervasive global shark mortality trends (Worm et al., 2013); 2) limited historical management of regional sharks and related impact (Raje et al., 2002; Akhilesh et al., 2014; Kizhakudan, Zacharia, Thomas, Vivekanandan, & Muktha, 2015; Varghese, Vijayakumaran, Tiburtius, & Mhatre, 2015); 3) national relevancy in the global shark harvest (Lack & Sant, 2011; Dent & Clarke, 2015); 4) geographic significance of study in terms of conservation and inquiry priority (Dulv et al., 2014; Dulvy et al., 2017); 5) indicators of overfishing and depletion in certain national fleets (inshore trawl primarily; Bhathal, 2014); 6) ambiguity in the relevant literature corpus regarding the actual, contemporaneous fishing levels and general significance of oceanic tuna longline fishery (John & Vergese, 2009; Pramod, 2010 & 2012, Greenpeace India, 2012; Pillai & Satheeshkumar, 2013; Bhathal, 2014; Hornby, Arun Kumar, Bhathal, Pauly, & Zeller, 2015a, 2015b); and finally, 7) limited raw observational data and/or data-sets gathered expressly to facilitate on-going shark status analyses (Smale, 2008; Musick & Musick, 2011); there exists probable cause for heightened interest in the status of shark stocks in the maritime exclusive economic claim (EEZ) of India. It is likely that the region's shark stocks are under significant (and likely unsustainable) depletion stresses and are trending inevitably towards collapse (Smale, 2008; Dhaneesh & Zacharia, 2013). However, the extent to which this assumption is correct remains largely unknown and potentially time-sensitive. As the second largest harvester of sharks, India needs information on the status of shark populations subjected to fisheries within its EEZ.

This study begins to fill this paucity of data by focusing on a high priority and little-known space; the oceanic longline fishery and affiliated shark bycatch mortality, which having established a proof of concept and viability in the target area of the India EEZ, may be scalable to the entirety of the under-assessed Indian Ocean basin, data availability homologies withstanding.

Broadly speaking, the focal objective of this study is to determine the species/stock status for a number of regional shark species in quantitative terms where none had previously existed. The results are envisioned to be sufficiently robust as to act as the informational basis for the consideration of sustainable management intervention or policy course correction, should such actions be found vital.

Addressing the question: "Is the country with the second highest global shark catch mirroring similar global trends of decline due to its marine fishing activity," at least in a partial and formatively useful way, is of primary interest to this research venture. A satisfactory answer must consist of the following: the explicit quantification of the impacts of fishing effort; biologically-based management reference points for the community of plausibly affected sharks within Indian waters, and ultimately a contemporaneous status determination on a per-species level.

Status assessments were performed for variety of shark species found in the Indian Seas, specifically the country of India's Exclusive Economic Zone. The conceptual foundation of the core status assessment is based on the SAFE protocol; designed and outlined in formative publications under the primary authorship of Shijie Zhou (Zhou & Griffiths (2008); Zhou, Smith, & Fuller (2007, 2009, 2011); Zhou & Fuller (2011); Zhou, Fuller, & Daley (2012)). The intrinsic draw and ultimate rationale for selection of the SAFE protocol as the primary kernel of this study's analytical program was its ability to produce stock specific harvest reference points for individual species with respect to a situation of data limitation. However, within the purview of this study, the SAFE protocol and its relevant equations were recast in an expressly probabilistic context., i.e., the majority of the operative variables within Zhou's data limited SAFE equations (specifically those relating to longline gear; see Ch. II) were expressed as fully random parameters linked by their given functional relationships with minor adjustments. Two separate Bayesian Hierarchical Models were constructed and run using the OpenBUGS statistical software to derive marginal posterior distributions of fishing mortality (F), and marginal posterior distributions of the following biological reference points: F_{msm}, F_{lim}, and $F_{crash.}$ Integration with respect to the marginal posteriors of the aforementioned parameters was accomplished via large iteration Monte Carlo Markov Chain (MCMC) simulation using a Gibbs sampling algorithm. Mean point values and credible intervals were determined via kernel density estimation of the marginal posterior density for target parameters. The relationship between these two values—that is, fishing mortality and the closest biological reference point—prescribes a specific sustainability status determination from Low-risk to Extreme High risk.

Background

The current best estimate of global shark biomass is roughly (21.6 Mt) (Worm et al., 2013). Global catch assessments estimate approximately 100 million sharks landed annually, exclusive of unregulated, unreported, and illegal captures. Estimates of total annual mortality have been placed around 100 million sharks in 2000, and about 97 million sharks in 2010, with a total range of possible values between 63 and 273 million sharks per year (Worm et al., 2013). Catch statistics for sharks are incomplete, and mortality estimates have not been available for sharks as a group (Dulvy et al., 2014). The global catch and mortality of sharks; inclusive of reported and unreported landings, discards, and shark-finning; has been estimated to be 1.44 million metric tons for the year 2000, and at only slightly less in 2010 (1.41 million tons; Worm et al., 2013). Previously, Clarke et al. (2006) used trade auction records from Hong Kong to estimate the total mass of sharks caught for the fin trade. Estimates ranged between 1.21 and 2.29 Mt (million metric tons) yr^{-1} with a median estimate of 1.70 Mt yr^{-1} in the year 2000, alluding to the troubling potential scenario that the biomass of sharks caught worldwide may in fact be three- to four-fold in excess of the summary statistics complied through voluntary submission by the United Nations FAO (Clarke et al., 2006), meaning that a large slice of the global shark harvest may be invisible to detection due to pervasive under- or misreporting by the world's most active shark fishing nations. In total, three independent estimates of the average exploitation rate ranged between 6.4% and 7.9% of sharks killed per year. This exceeds the average rebound rate for many shark populations, estimated from the life history information on 62 shark species (rebound rates averaged 4.9% per year; Worm et al., 2013).

The global shark fishery is primarily driven by 20 countries, with Indonesia (13%), India (9%), Spain (7.3%), Taiwan (5.8%), and Argentina (4.3%) contributing most to shark landings (Dent & Clarke, 2015). Thirteen shark harvesting countries are known to have national plans of action for conserving and managing sharks (NPOA-Sharks). However, no substantial evidence exists to indicate that NPOAs are increasing the effective management of shark fisheries in their countries (Lack & Sant, 2011), however it may be too early to make claim in circumstances of most recent implementation.

At a general level however, species-specific catch statistics are lacking from most shark fishing countries, although data may be available for aggregations of species in some higher groups (orders or families; Lack & Sant, 2009). Species catch data aggregated into higher groups can easily mask declines of individual species within the groups. In terms of total catch diversity profiles, examples are many of larger species, which grow at slower rates, being replaced by smaller species, which grow at faster rates, with no apparent changes in landings data for the group (Dulvy & Forrest, 2010). Whereas directed fisheries have been the cause of stock collapse in many species of elasmobranches, capture in mixed fisheries and non-target bycatch in fisheries directed toward more productive teleosts are the biggest global threats to elasmobranch stocks (Musick, 1999; Stevens et al., 2005), as they may often be retained as valuable bycatch

(Stevens et al., 2005) even if technically incidental. This mortality vector defines the express focus of this study, specifically the case of shark bycatch within the oceanic long-long fishery primarily targeting yellowfin tuna.

Nominal catches of sharks and rays by species in the Food and Agriculture Organization of the United Nations (FAO) FISHSTAT database (FAO, 2011-2018) are difficult to interpret due to the uneven categorization of catches among landing countries. Some countries provide species-specific catch data, whereas some of the most important countries with the highest catches, such as India, simply report “sharks, rays, skates, etc.” In 2007, only 20 percent of the reported catch was identified to the species level (Musick & Musick, 2011).

The Economy of Shark Fishing

Due to the low economic value of sharks and rays, few resources have been put into the collection of fisheries landings data (FAO, 2009). This has been compounded by illegal, unreported and unregulated (IUU) fishing, particularly in regard to shark fins (FAO, 2009). Catch per unit effort (CPUE) trends from either fisheries or fisheries independent data are available for only a handful of stocks, and most recent CPUE analyses of elasmobranch stocks have shown declines (Dulvy & Forrest, 2010). Formal stock assessment models have been produced for even fewer stocks. A key problem is the incomplete reporting of shark catches to the United Nations Food and Agriculture Organization (FAO), which tracks the status of fisheries worldwide. Caught sharks are often not landed and are instead discarded at sea, with such discards not usually reported to national or international management agencies unless there are trained observers on board. Compounding this problem is the practice of shark finning, where the animal's fins are removed prior to the body being discarded at sea (Worm et al., 2013). In addition to calculation of IUU, which is underrepresented by virtue of design, the remainder of total shark mortality pathways are parsed respectively (Figure 4).

As previously mentioned, in recent times sharks have started to be targeted more for their fins due to growing demand from the Asian market and its growing economic affluence (Ng, 2011). "Shark finning", is considered unsustainable because it exploits only fins, which average 5–16 % of the body mass (Ariz, Delgado de Molina, Ramos, & Santana, 2006), wasting the rest of the shark body. Without fins, sharks are unable to swim and will sink to the bottom to die (Ng, 2011).

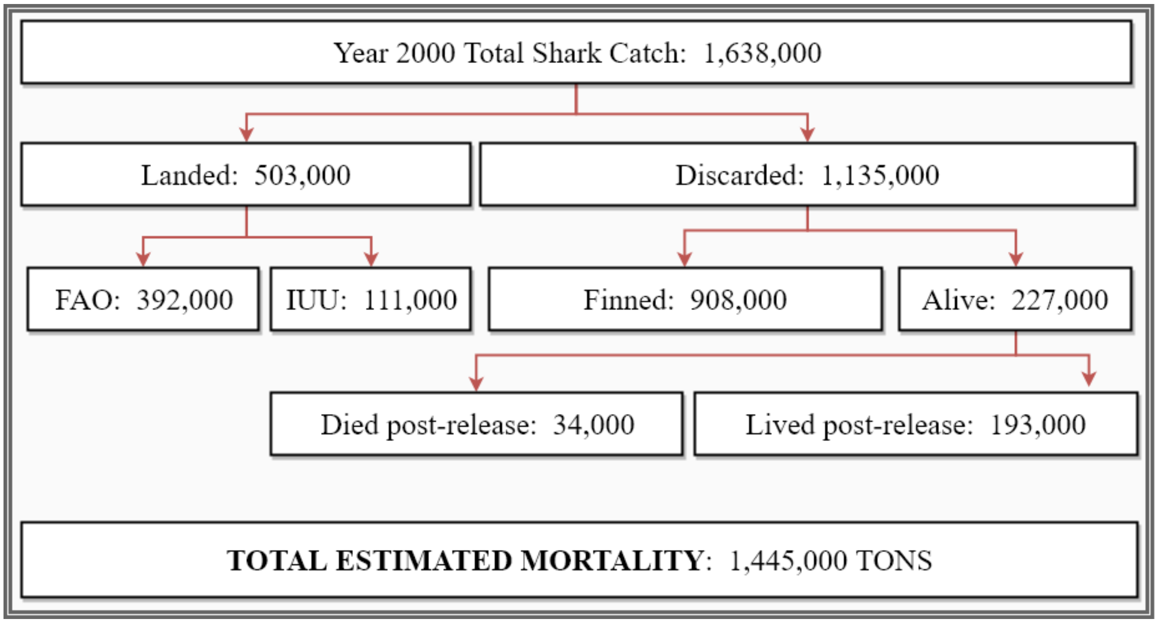


Figure 4. Estimating global shark mortality for the year 2000. Included are reported (from FAO) and illegal, unreported, and unregulated (IUU) landings as well as shark discards. Total mortality was calculated as the total catch minus the number of sharks which survived discarding. All figures were rounded to nearest 1000 metric tons. Figure was reconfigured from Worm et al. (2013).

The shark fin trade increased from a total of 4,907 mt in 1987 to 13,614 mt in 2004 globally (Clarke et al., 2006). More than 90 % of shark fin imports reported to the FAO in 2004 were to Hong Kong (58 %) and China (36 %), where the fins are used as the main ingredient of a traditional soup (Wild Aid, 2007). According to Dell'Apa, Smith, & Kaneshiro-Pineiro (2014), even though shark finning is prohibited in many countries, high prices for fins from the Asian market help maintain the international black-market and poaching. It is further suggested that traditional shark fin bans ultimately fail to recognize that the main driver of fin exploitation is the linkage of commercial demand to cultural beliefs about the prestige of sharks in traditional Chinese society.

Perspectives on Shark-fin Trade from National Sources

Today, while India ranks second in global shark production, shark fin trade from the country does not appear to be a matter of alarming priority if we are to believe the assessment of the recently published National Action Plan on Sharks (i.e., Kizhakudan et al., 2015). Since shark flesh fetches relatively good value in an Indian context, gillnet and small-scale longline units land sharks with fins attached, and the finning is done at landing centers or processing plants, rather than through the much more controversial practice of at-seas finning and discard (Varghese et al., 2015). FAO statistics indicate that while India's shark production is about 9% of the global production, the country's shark fin exports form 6% of the global figure.

Shark fins are one of the commodities in great demand in international markets. The shark fins find their way to East Asia to meet the demands of an expanding international shark fin market. Hong Kong, China and Singapore are the major demand centers for shark fins. As per MPEDA statistics, India exported 195 tonnes of shark fins worth US $ 14.99 million in 2011 against 960 tonnes worth $2.74 million in 1998 (Kizhakudan et al., 2015).

The quantity of shark fins exported from India in 2013-14 stood at about 122 tonnes. Mumbai and Chennai have been the major centers for collection, processing and export of shark fins and fin rays. The trend in recent years, however, indicates an initial increase from 2008-09 to 2010-11, followed by a considerable decline in 2013-14, should we be considering these fin reports as accurate. Quality and price of the fins are decided based on the species from which the fins are sourced. When the fin trade was still legal in India as of 2015, for the years preceding the ban India had exported almost all shark fins it produced in what was a largely informal and unregulated sector, and many observers believed that official export data greatly understate actual shark fin exports. Hausfather (2012) estimated Indian shark fin exports, one based on projected shark fin production from the Food and Agriculture Organization (FAO) recorded landings data and the other based on recorded Hong Kong imports from India. The comparison between the data showed that actual exports are likely many times greater than officially recorded amounts (Hausfather, 2012). Whether or not shark finning has gone underground now that there is a full ban in place is poorly known, even despite the claims to the contrary by prominent sources in the field (that is, a lack of finning), but it should be considered plausible.

India Shark Fishing Sector in Focus

India has an exceptionally large exclusive maritime claim, which includes its mainland EEZ as well as an extensive maritime area around the Union Territory of the Andaman & Nicobar Islands, which is an archipelago that straddles the east/southeast part of the Bay of Bengal and much of the Western Andaman Sea, neighboring Sumatra in the South and Myanmar in the East (Figure 5). Under most circumstances, a nation's EEZ stretches from its coast 200 nautical miles (approx. 370km) out to sea; however, many exceptions exist, such as when the waters must be shared or split between countries or in relation to territorial islands.

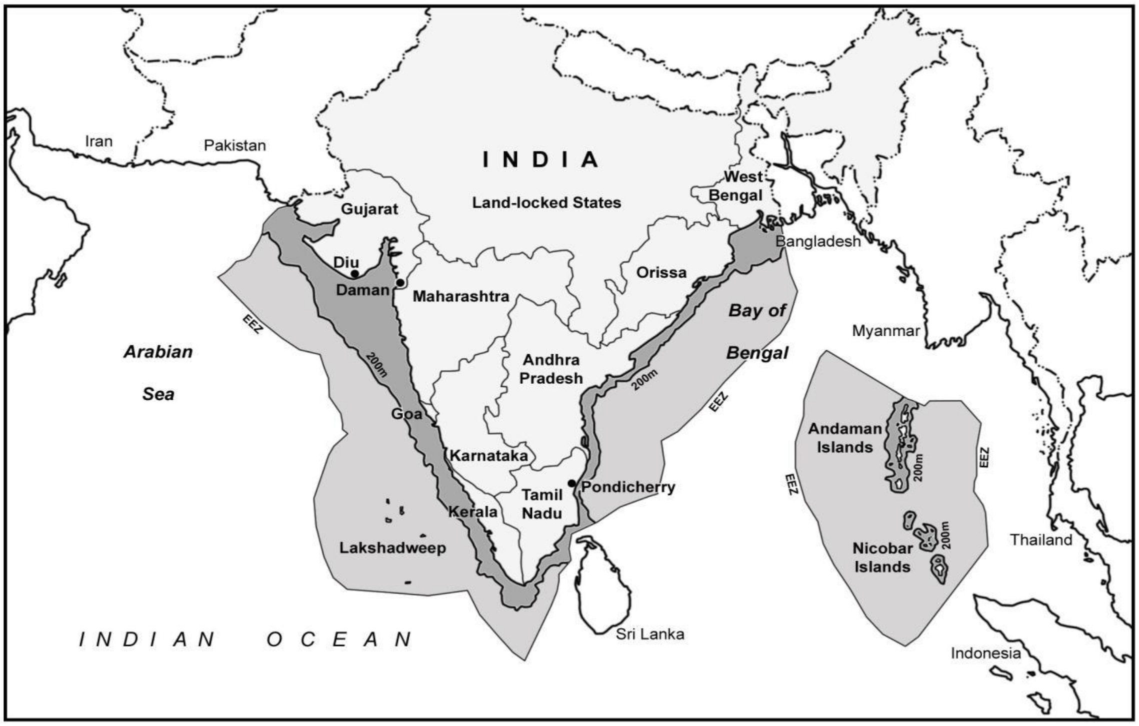


Figure 5. Map of India, EEZ, & maritime neighborhood. The shelf (dark grey) and its 200 m depth limits are also shown, along with the rest of the Indian EEZ (light grey).

By the dawn of the 2000s, a new phase in the Indian marine fishery had emerged characterized by stagnating or even declining fish catches, depleted fish stocks and increasing conflict over fish resources (Bhathal, 2014). As a result, the focus of the Indian government has pivoted once again towards renewed development of oceanic and deep-sea fisheries, to diversify the fishing operations of the domestic fleets, with a focus on increasing tuna catches for export (Pillai, 2006; Main, Saba, Sofi, & Azhar, 2013; James, 2014; DAHD&F, 2014). The wisdom and true contemporary efficacy of this sentiment is less clear than it perhaps may have been in decades past, and although defines the will of many reasonable actors, it has been recently called into question (John & Varghese, 2009; Pramod, 2010, 2012; Greenpeace India, 2012; Pillai & Satheeshkumar, 2013; Bhathal, 2014; Hornsby et al., 2015a, 2015b; Rajasean, 2015).

Although India has a robust coastal fishing sector, it has not historically had a large fleet of domestic origin operating in the open ocean—that is, the zone >50km offshore and 50-200m in depth where the continental shelf generally begins to drop off formally (Chuenpagdee, Liguori, Palomares, & Pauly, 2006; Spalding et al., 2007). At this point, ocean benthic or sea floor existence become less influential to species inhabiting the water column, and a defined new ecosystem begins to emerge with separate constraints on the ecology of the species operating within it.

India is one of the major shark fishing nations in the world and currently stands at the second position, next only to Indonesia. Shark landings include catches of true sharks, rays and guitarfishes. According to FAO statistics, India’s contribution to the annual average global catch of sharks during 2000-2009 was 9% (Lack & Sant, 2011; Dent & Clarke, 2009).

Historically, artisanal fishermen in India have been conducting shark fishing in a sustainable way in the form of a sustenance fishery. Shark landings by the mechanized sector were mainly in the form of bycatch from inshore fisheries; however, targeted shark fishing as it exists in its current permutation started when market demand for this commodity set in. In recent years, increases in demand for sharks in international markets, especially for the fins, has increased the number and efficiency of fishing boats, directed fishing and expansion of fishing areas, as well as multi-day, deep water shark fishing, which has become a prevalent practice in Indian waters (Akhilesh et al., 2011). The cumulative effect of these factors led to an increase in fishing effort and, thereby, an increased yield of shark catches initially. However, consistent decline in catch and catch rate in the last one decade has raised serious concerns over the resource and the long-term viability of its fishery (John & Varghese, 2009).

Overview of Indian Shark Harvest

The annual landing of sharks in India during the period 1950-2016 is seen to have fluctuated between 29,000 t and 75,000 t, with the annual avg. being 52,640 t (Figure 6). Although the trend appears to be increasing, the landings during the 1960 s and early 1970s were mostly by the artisanal sector. The effect of mechanized fishing operations is noticed from the mid-1970s, with the landings showing an initial increase.

The annual landing of sharks in India in 2013 was 46,471 t constituting 5% of the demersal and 1.23% of the total marine fish production in the country (Kizhakudan et al., 2015). Of the exploited shark resources, sharks constitute 44%, rays, 52% and skates, 4%. While annual shark landings have hovered within the range of 50-70 thousand tonnes over the last 29 years; the share of sharks in total fish landings has declined by more than 64% from 1985 to 2013. Peak landing was observed in the year 1998, when it almost touched 75 thousand tonnes. Mohanraj, Rajapackiam, Mohan, Batcha, & Gomathy (2009) mention an increasing trend in elasmobranch catches in India from 27.4 thousand tonnes in 1961 to 49 thousand tonnes in 2006. However, the trend from 1985 to 2013 has

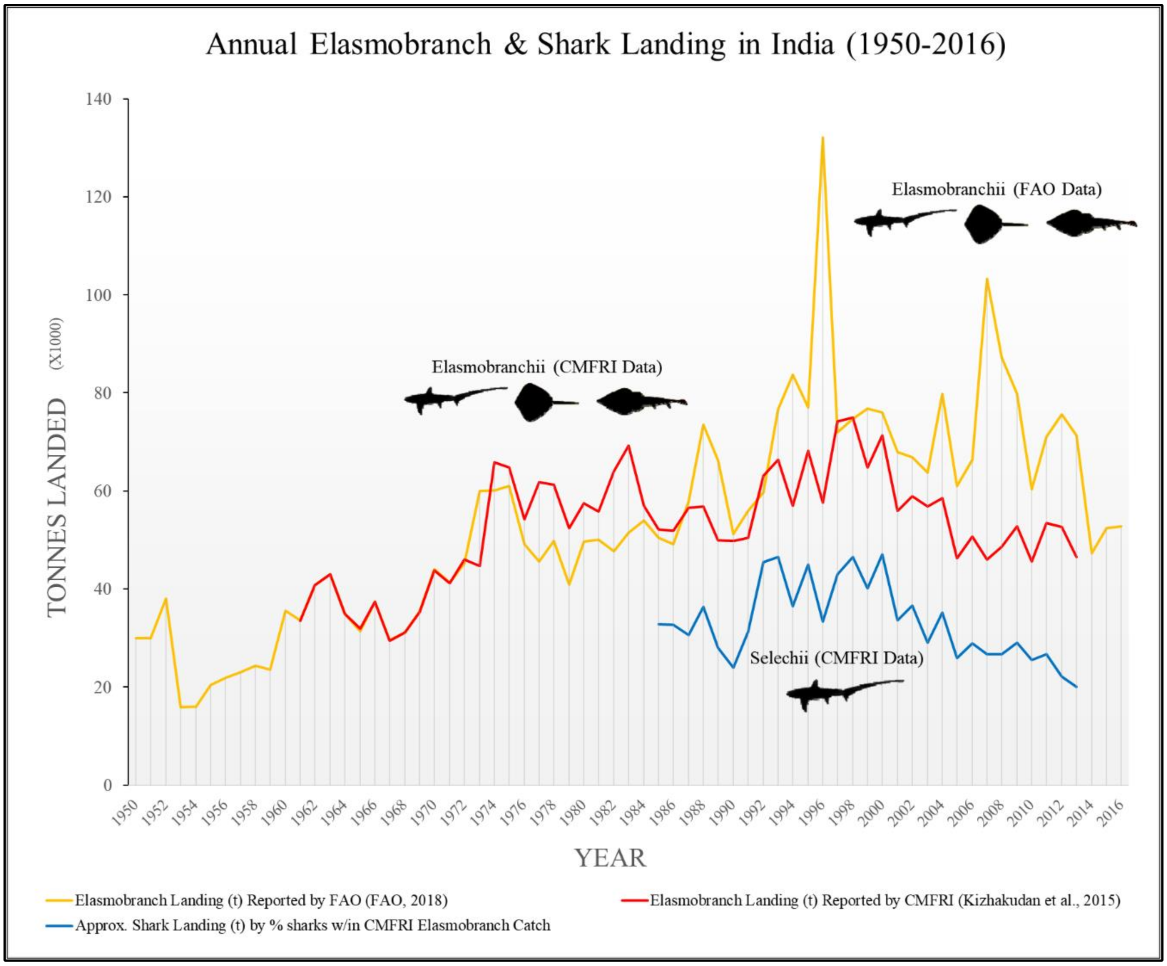


Figure 6. Annual elasmobranch & shark catch in India (1950-2016). Approximate true Shark (Selechii) catch (t), the line in blue, is taken from (%) of total Elasmobranch catch defined in Kizhakudan et al. (2015); per year metrics for Selechii (%) are superimposed on the total Elasmobranch catch in (t) to calculate approximations for true shark (Selechii) catch in (t).

been fluctuating with landings peaking at >70,000 tonnes in 1997, 1998, and 2000 (Kizhakudan et al., 2015).

The increase in shark landings during 1997-2000 is the result of intentional whale shark hunting, in high intensity, along the north-west coast of India (Kizhakudan et al., 2015). However, the contribution of sharks to the total marine fish production in the country had already slipped from 3.43% in 1985 to 2.81% in 1998 and stood lowest at 1.23% in 2013, indicating a disproportionate growth between total marine fish landings and shark landings (Kizhakudan et al., 2015). While sharks formed only sustenance fisheries in some parts of the country or were taken as bycatch in coastal fisheries during the 1980s and early 1990s, targeted fishing, particularly for sharks, was initiated from the late 1990s with increase in demand for shark products in international markets.

According to the 2015 NPOA-Shark report produced the CMFRI (i.e. Kizhakudan et al., 2015), sharks were the largest contributors to the landings during 1985-2011 forming >50% of the landings (average 59.9%). During 2012 and 2013 however, their contribution fell to under 50% (average 44.2%). Shark landings showed a fluctuating yet increasing trend from 33,112 t in 1985 to 47,207 t in 1998 followed by a sharp decline to 21,138 t in 2013 (Kizhakudan et al., 2015). Falling shark landings is a matter of concern since it would take many years for depleted shark stocks to recover. Turning back to Figure 6, although the FAO and CMFRI data initially track with reasonable parity, the significant spike in the 1996-1997 year in the FAO data above and beyond the CMFRI data is questionable. Since the CMFRI is the contributing source to FAO, the former may likely take priority. Given that the FAO data for this year in particular is very close to double that of the CMFRI value, it may simply be a clerical oversight which occurred at some point in the transcription process resulting in double counting on the year. At present, the rationale however for the divergence in these two data sets remains outstanding.

In 1996, Mathew, Devadoss, Vivekanandan, Ferozkhan and Zacharia (1996) estimated the potential yield of sharks resident within Indian fisheries to be 65,000 metric tonnes within 50 m depth zone and 103,000 metric tonnes beyond 50 m depth zone. Later, potential yield of true sharks in the continental shelf of the Indian EEZ was estimated to be 45,064 t, and that of pelagic sharks beyond the continental shelf, 26,200t (CMFRI, 2000). These estimates were further revised in 2011 as 85,882 t for sharks and 48,721 t for true sharks in the Indian EEZ up to 100 m depth. Landing data assimilated by the Central Marine Fisheries Research Institute [of India] (CMFRI) indicate that the potential yield estimated for sharks from beyond 50 m depth zone has not been reached. Instead, it appears that the 50 m zone has been fished heavily and with falling landings, there is a high probability of depletion of coastal species of sharks from these areas.

Continuing with the investigation of regional dynamics in the shark fishing sector, increased resolution is found through the delineation of the Indian EEZ in respect to its quadrants and two principal coasts. At a glance, surveys to mark the distribution and abundance of sharks in the Indian EEZ have recorded high catch rates off the north-west zone with an equitable mixture of true sharks and rays in the area; hence, historically the north-west zone is the most substantial in terms of shark production (Mathew et al., 1996). The north-east zone has been shown to have a much higher concentration of sharks in shallow waters and in general surveys have indicated that west coast resources are deeper whereas most of the east coast resources are shallower in nature. At present, Gujarat and Maharashtra on the west coast and Tamil Nadu, Puducherry and Andhra Pradesh on the east coast contribute to the fishery; though, with the limited production of skates and decline in shark catches, there remains an urgent need to reassess the potential for elasmobranch fishery in Indian waters.

The west coast of India has remained more productive than the east coast, contributing, on average, 68% of the annual landings of true sharks and 66% of the annual skate landings in the country. The east coast on the other hand has remained the higher contributor of ray landings with annual average contribution of 72% (Table 1). A five-yearly profile of coast-wise contribution to the landing of sharks indicates an increase in the contribution of the west coast from 66.7% in 1985-90 to 74.1% in 2010-13. In the case of skates there has been a decline from 72.7% in 1985-’90 to 62% in 2010-13. The contribution of the east coast to the landing of rays has shown an increase from 66.1% in 1985-’89 to 79.7% in 2010-13 (Kizhakudan et al., 2015).

Table 1. Coast-wise landing of sharks, skates, and rays in India (1985-2013).

Annual average landing (t)	Sharks	Skates	Rays
India	33982	2633	20234
West coast	23264	1722	5498
% in all-India average	68	66	28
East coast	10718	912	14736
% in all-India average	32	34	72

Recompiled from Kizhakudan et al. (2015).

The states of Gujarat and Maharashtra on the north-west coast have remained the major players in this arena, followed by Kerala on the south-west coast. The north-west coast

(Gujarat, Daman & Diu and Maharashtra) contributes 57% of the shark landings, while the south-east coast (Tamil Nadu & Puducherry and Andhra Pradesh) contributes 21%. The south-west (Goa, Karnataka and Kerala) and the north-east (Orissa and West Bengal) contribute 12 and 10 % respectively. In an earlier study, Vivekanandan & Sivaraj (2008) also reported that the north-west coast contributed 57% of the shark landings in the country. The contribution from the south-east coast reported by them was higher at 25 % when compared to the current average of 21%.

However, the nature of shark fishing and landings along the Indian coast is such that sharks caught from one part of the coast are often landed elsewhere (Kizhakudan et al., 2015), and this may frequently be the case with the oceanic sector as well, in which many of the actors are international and rarely utilize the Indian domestic processing and thus record keeping apparatus. Hence a delineation of landings as caught from west or east coasts may often be misleading. Viewed from this aspect, it may be better concluded that the contribution from the two coasts has not changed significantly over the years catch-wise.

Changes in landing patterns may be influenced by market demand, especially for export. Rapid Stock Assessment (RSA) of sharks based on data for the period 1985-2013 and following the classification criteria suggested by Mohamed et al. (2010) indicates the delicate status of sharks in Indian waters. Sharks were either “less abundant” or “declining” along the Indian coast, except in Tamil Nadu & Puducherry, where the 3-year avg. was only 7.6% of the historic maximum, and thus classified as “depleted” (Table 2).

Table 2. Results of the Rapid Stock Assessment (RSA) of sharks, skates, and rays along the Indian coast.

Resource	Coast	HMC (t)	3YA (T)	% of HMC	Status
SHARKS	Gujarat	27985	11069	39.6	DC
	Maharashtra	12929	4034	31.2	DC
	Karnataka & Goa	2829	749	26.5	DC
	Kerala	5151	2328	45.2	DC
	Tamil Nadu &	10934	827	7.6	DP
	Andhra Pradesh	6871	1572	22.9	DC
	Orissa	3077	1128	36.6	DC
	West Bengal	5482	3196	58.3	LA
SKATES	Gujarat	1412	1132	80.2	A
	Maharashtra	1927	131	6.8	DP
	Karnataka & Goa	307	229	74.6	A
	Kerala	875	257	29.4	DC
	Tamil Nadu &	1613	426	26.4	DC
	Andhra Pradesh	685	119	17.4	DC
	Orissa	351	6	1.6	C
	West Bengal	601	57	9.4	DP
RAYS	Gujarat	7012	2446	34.9	DC
	Maharashtra	2660	498	18.7	DC
	Karnataka & Goa	2398	345	14.4	DC
	Kerala	4070	1082	26.6	DC
	Tamil Nadu &	16429	10487	63.8	LA
	Andhra Pradesh	9971	6746	67.7	LA
	Orissa	1971	906	45.9	DC
	West Bengal	2059	831	40.4	DC

HMC - Historic Maximum Catch (1985-2013); 3YA - 3-year average (2011-13). Data recompiled from (Mohamed et al., 2010; Kizhakudan et al., 2015).

Elasmobranch Species Composition of the Indian Marine Fishery

In the early 2000's, Raje et al. (2002) listed 66 species of sharks occurring in the Indian seas. More recent surveys over the past decade have increased that number moderately, although additions have come mostly in the form of proportionally infrequent or newly discovered shark species, particularly of deep-water origin (Vivekanandan & Sivaraj, 2008; Akhilesh et al., 2011; Akhilesh et al., 2014). The most recent authoritative survey by Kizhakudan et al. (2015) lists 88 species of true shark in the Indian Seas (out of 160 Elasmobranchii species in total).

Of these 160 species of Elasmobranchs which are known to occur in India's commercial fishing zone, 88 species are sharks belonging to 44 genera from 21 families, 53 species are rays belonging to 19 genera from 10 families and 19 species are skates belonging to 10 genera from 4 families. Regarding the sharks in particular, 11 species are predominant in the fishery and 20 are of common occurrence in the landings along the coast. Requiem sharks (Carcharhinidae), Hammer-heads (Sphyrnidae), Threshers (Alopiidae), Mackerel sharks (Lamnidae), Bamboo sharks (Hemiscyllidae) and Hound sharks (Triakidae) are the major contributors to the commercial fishery specifically (Kizhakudan et al., 2015). However, these species low biological productivity makes them vulnerable to fishing, with limited chance for recovery.

Carcharhinidae comprised 84.6% of the true sharks landed during 2007-2013 in the country. Out of about 31 species of requiem sharks occurring in Indian waters, at least 21 species are regularly fished. Shark landings along the north-west coast of the country are dominated by the milk sharks *Rhizoprionodon oligolinx* and *R. acutus* and the spade-nose shark *Scoliodon laticaudus*. Landings along the southwest and south-east coast, however, are dominated by requiem sharks of the genus Carcharhinus. Landing of thresher and mackerel sharks and the oceanic white tip shark *Carcharhinus longimanus* has been found to be increasing in recent years, with increased operations in oceanic waters.

Vivekanandan & Sivaraj (2008) noted a shift in the shark fishery from an artisanal coastal fishery towards an oceanic fishery employing drift gillnets and hooks & lines operated from mechanized craft. Maximum exploitation of large sized sharks beyond near shore coastal fishing zones is done mostly by the shark fishing fleet of Thoothoor in terms of targeted effort (Kizhakudan et al., 2015). However, the falling trend in both the contribution of sharks to the total marine fish landings and the share of true sharks in the total shark landings indicate that despite extension of fishing grounds, exploitation of oceanic waters and increase in the species diversity in shark landings, the quantum of catch appears to be stagnating in the Indian EEZ (John & Varghese, 2009). Landings of several high-value carcharhinid sharks have also notably dwindled at some of the major fish landing centers like Chennai in the recent years. On the other hand, there is a spurt in shark landings and diversity at Cochin, primarily because it has become one of the major landing sites for sharks caught from different zones along the Indian coast. In 2013, true sharks constituted almost 50% of the total shark landings at Cochin while at Chennai they formed only 5.9% (Kizhakudan et al., 2015).

As noted previously, although reports indicate an increase in number of shark species in Indian waters, new additions to the list are mostly deep-water forms (Akhilesh et al., 2011), very few of which are commercially exploited, at least traditionally. However, Akhilesh et al. (2011) noted the significant emergence of a targeted fishery for gulper sharks (*Centrophorus spp*.) as early as 2008–'09 based out of Cochin which did not exist before, with longline effort targeting depths >300–1000 m. Emergent fisheries notwithstanding, members of the family Carcharhinidae and Sphyrnidae remain major contributors to India's commercial shark fishery, with minimal change in species composition in the last two decades in this respect.

Among the hammerheads *Sphyrna lewini*, *Sphyrna mokarran*, and *Sphyrna zygaena*, all three of which have been included in the CITES Appendix II listing which came into effect in September 2014, *S. lewini* and *S. mokarran* are classified as "Endangered" and *S. zygaena* is classified as "Vulnerable." The milk shark *Rhizoprionodon acutus* and the grey sharpnose shark *Rhizoprionodon oligolinx* which contribute to the major share of commercial shark landings in India, particularly from the north-west coast, are species of "Least Concern." However, in many cases IUCN classification is based on an assessment of the global stock status of each species and need not necessarily reflect the stock status in Indian waters.

In terms of national shark conservation foci, the Pondicherry shark (*Carcharhinus hemiodon*), Ganges shark (*Glyphis gangeticus*), speartooth shark (*G. glyphis*), and whale shark (*Rhiniodon typus*) are protected under Schedule I of the Wildlife (Protection) Act, 1972, but these species, apart from the whale shark, are of coastal or insular distribution (John & Varghese, 2009). Pillai & Parkal (2000) note that the fins of six species in particular are being collected from Indian seas and exported: Smooth Hammerhead (*Sphyrna zygaena*), Milk shark (*Rhizoprionodon acutus*), Spadenose shark (*Scoliodon laticaudatus*), Black tip reef shark (*Carcharhinus melanopterus*), Sicklefin lemon shark (*Negaprion acutidans*), and Whale shark (*Rhiniodon typus*). The distribution of Indian Elasmobranch classified under IUCN categories indicates that 24% of the species in Indian waters are "Near Threatened" and 26% are "Vulnerable." About 24% are listed as "Data Deficient", 9% as "Not Evaluated," 3% as Critically Endangered" (Kizhakudan et al., 2015).

Of the 160 species of Elasmobranchii, fishery information is available for 141 species (Kizhakudan et al., 2015). Maximum exploitation is done by mechanized trawl net, gill net and line gear operations. As mentioned before, the finning of sharks is taking place on a large scale because of the increase in demand for shark fins in China primarily (Verlecar, Snigdha, Desai, & Dhargalkar, 2007)., noting that a full ban has been in place on the export of shark fins in India since February 2015 (Kwok, 2016).

Key Fisheries-Independent Longline Survey and Data Set of John & Varghese (2009) for the Indian Seas

One of the most recent and comprehensive longline surveys of the state of shark stocks in the Indian seas was published by John & Varghese (2009). Using the metric of Catch per Unit Effort (CPUE), which is the number of landed specimens per specified number of hook cast (No./100 hooks) and considered an index of abundance, the study provides a species-level catch-series and assessments from the period from 1984 to 2006. A total of 3.092 million hooks were operated in the survey covering the Arabian Sea as well as Bay of Bengal and the Andaman Islands between latitude 05º–23º N and longitude 64º–96º E. Indications of significant fishing pressures emerged from the study, the most alarming scenario being in the west coast as well as the east coast where the average CPUE recorded during the last five years was less than 0.1%. The sharp fall in the CPUE along the east coast occurred in 1990–91 and along the west coast in 1992–93. In the waters surrounding the Andaman and Nicobar Islands, the steep decline was witnessed in the year 1996–97 (John & Varghese, 2009). The percentage of catch by species in the survey is further represented subsequently (Table 3).

Table 3. Species composition of sharks recorded in tuna longline survey in the Indian EEZ (1984-2006).

	Percentage by Region		
Species	West coast	East coast	A & N
Pelagic thresher shark (*Alopias pelagicus*)	5.7	10.3	26.9
Bigeye thresher shark (*Alopias superciliosus*)	–	4.2	0.6
Thresher shark (*Alopias vulpinus*)	0.5	2.4	11.8
Alopias spp.	0.3	–	–
Blacktip shark (*Carcharhinus limbatus*)	26.7	17.0	5.8
Hard-nose shark (*Carcharhinus macloti*)	1.0	–	0.1
Spottail shark (*Carcharhinus sorrah*)	5.7	–	25.9
Whitecheek shark (*Carcharhinus dussumieri*)	4.1	–	–
Black reef shark (*Carcharhinus melanopterus*)	8.2	47.3	0.6
Silky shark (*Carcharhinus falciformis*)	6.9	–	–
Silvertip shark (*Carcharhinus albimarginatus*)	1.3	1.8	4.8
Oceanic whitetip (*Carcharhinus longimanus*)	–	0.6	4.7
Carcharhinus spp.	1.8	–	–
Tiger shark (*Galeocerdo cuvier*)	1.0	1.2	4.1
Shortfin mako (*Isurus oxyrinchus*)	1.8	0.6	1.8
Scalloped hammerhead (*Sphyrna lewini*)	0.3	6.1	
Smooth hammerhead (*Sphyrna zygaena*)	1.0	0.6	5.0
Great hammerhead (*Sphyrna mokarran*)	33.7	7.9	7.9
Blue shark (*Prionace glauca*)			
Milk shark (*Rhizoprionodon acutus*)			
Broadfin shark (*Lamiopsis temmincki*)			
Spade-nose shark (*Scoliodion laticaudus*)			
Zebra shark (*Stegostoma fasciatum*)			
Unspecified sharks			

A & N = Andaman & Nicobar Island. Table reproduced from John & Varghese (2009).

Evolution of Marine Fishery in India

The history of maritime activity and coastal resource usage in India is long and well developed, dating back some 5000 years (Jhingran, 1975) and prevalent in cultural memory via prominent references in autochthonous religious mythology (e.g., Matsyavathara, the fish avatar of Vishnu) (see Figure 20). Records indicate that in the 18th century salt-fish trade flourished along the western coast of India (Silas, 1977). The first prominent acknowledgment of the Indian Seas' system in terms of resource management and records keeping would occur through the "The Indian Fisheries Act" in 1897; though, additional substantive reforms would mostly be postponed until after national independence in 1947. The majority of modern innovation and evolution in the marine fishery would take place after the shrugging of English imperial dominion, and thus harken the entrance of the sector into the fully modern era, though with substantially syncopated development. Access to international knowledge exchange through the United Nations and other specialized, cooperative programs would introduce various innovations in the 1950's and 1960's. In the 1950's, interest was seen worldwide in the development of small boats, and the FAO World Fishing Boat Congress of 1953 in Paris and Miami further codified this sentiment (Chidambram, 1982); around this time India would begin proactively seeking out technology exchange opportunities on the international stage. Other methods of fishing, such tuna lining (introduced in 1963 [Dixitulu, 2002]) and purse seining were introduced in subsequent years; although, trawling for shrimp would emerge in this era as the formative driver of the national marine fishery sector given the desirability of the product in international markets, which continues to the present day. In early 1970s, fiberglass-reinforced plastic (FRP) boats were introduced in India. A significant push for the motorization of the artisanal sector began in 1980's as a program of the Seventh Five Year Plan (GOI, 1985) with options to engage in coop-financing. The introduction of outboard motors in an accessible way initiated a revolution in fishing in the country, greatly increasing efficiency in virtually all components of the activity. Commercial tuna fishing in India commenced in 1985 and tuna longlines operated in Indian waters under Indian-owned, joint-venture and leased foreign vessels scheme targeting scombroids, i.e., tunas, seerfishes and billfishes (Somvanshi & John 1996), with many different countries entering into joint ventures with India over time. Steadily, various advanced designs and sizes of mechanized vessels were launched, resulting in multiday fishing in the late 1990s. (Sreekrishna & Shenoy, 2001). By the early 2000's increasing numbers of deep-sea vessels were clearly competitors of the artisanal sector, which caused unrest and the eventual regulations enacted by the states to control such operations. In December 2006, the DAHD&F passed an ordinance on joint ventures, stating that the operation of deep-sea fishing vessels would be permitted in Indian EEZ under joint ventures for only tuna longlining, squid jigging, pole and line fishing and purse seining (Rao, 2009a, 2009b).

Indian Fleets & Fishing Practices

India's marine fishery is typically multi-species, multi-gear, and multi-ground. Different gears are often operated from the same boat, alternately or simultaneously, depending on the fishing season and resource availability. Fishing boundaries between states are non-existent and catch from different grounds are often landed together at a particular landing center, making it difficult to assess the actual area of catch. Enquiry based information is the only way. Log book maintenance by small scale commercial fishers is not a mandatorily observed practice, and access to logbooks, if maintained, is often difficult. There is no system of log book recording in artisanal fisheries.

In terms of domestic actors, information on shark fishing grounds is difficult to obtain and collate since directed fisheries on a relatively large scale is mostly restricted to the shark fishing fleet of Thoothoor, which lands most of the catch in Cochin Fisheries Harbor and some other ports, even if the fishing ground is far away.

Historically, sharks have always figured significantly in India's artisanal fishery. A lucrative fishery for sharks existed along the north Malabar coast before mechanization set in, where sharks formed the mainstay of the marine landings. However, technological advancements in fishing craft, gear and methods have improved the efficiency and extent of shark fishing operations. At present, sharks are taken by a combination of different types of crafts and gears. Based on this, the fishery can be classified into three major sectors - mechanized (large boats with inboard engines), motorized (boats with outboard motor) and non-motorized. Trawl fishing, offshore large gill net operations and longlining are mechanized sector fishing. Most of the small-scale coastal fishing operations using gill nets are done by the motorized sector. Hook & line operations, cast nets, small gill nets and traps are operated by the non-motorized sector in the inshore waters.

During 1985–2013, the mechanized sector contributed the major share (71%) of the sharks landed; the motorized sector accounted for 22% and the non-motorized sector, 7%. A five-yearly analysis of the sector-wise contribution to shark landings (four years in the last period) indicated a nominal increase from 70% in 1985–'89 to 80% in 2010–'13 in the mechanized sector landings (Kizhakudan et al., 2015). The contribution from the motorized sector however, increased from 6% in 1985–'89 to 31% in 2000–'04 and decreased to 20% in 2010–'13. The non-mechanized sector (artisanal fishery) which contributed about 24% of the shark landings in 1985–'89 has now been relegated to the background, with the contribution being under 0.5% (Kizhakudan et al., 2015).

Pelagic longline fisheries are a significant source of catch for many species of sharks. Bonfil (2000) claimed that while less indiscriminate than some other fishing methods, the widespread use of longlines, combined with the sheer length of lines and the number of hooks utilized, means that more ocean-going (pelagic) sharks are caught as bycatch in longline fisheries than in any other fisheries on the high seas. Pelagic longlines consist of a mainline that can stretch for tens to hundreds of kilometers (Xu, Zhu, & Song, 2006), suspended by floats with branch lines, which are vertical lines attached to the mainline by a clip or swivel with a hook suspended below. Catches in this sector, which have historically had a large contribution from international operating under special promissory schemes from the government of India, rarely land there catch at Indian domestic ports, and thus their contribution is highly masked or tallied in terms of other countries totals (Greenpeace India, 2012).

Drift gill net is a type of fishing gear designed to entangle or ensnare fish by keeping the net near or at the surface with floats and allowing it to freely drift with the currents. Bottom or mid-water gill nets, which are weighted so that they fish at or near the bottom and are generally anchored to prevent drifting, can also catch a variety of shark species. Studies on gill nets report high mortality rates, especially among certain species of the requiem and hammerhead sharks. Gill nets and longlines cause species-specific mortality and are used selectively depending on the availability of sharks in different seasons and areas. Generally long soak times (the length of time a fish is kept on fishing gear before being brought up) in bottom longline fisheries have also been linked to higher mortality rates among some shark species (Raje et al., 2002).

Trawls are funnel-shaped nets that also catch sharks as bycatch. These nets have two wings of varying lengths that extend the net opening horizontally, and they can be pulled along the bottom. The trawl-nets used in India are of high-opening type, capable of taking catches from any level in the mid-water, including the surface water. Exclusive shark fishing as a practice exists only to a limited extent in India, and often sharks are caught as bycatch from trawl, gill net, hook & line and longline operations. Even in directed line fishing, the target species is changed between sharks and tunas by using different types of hooks.

Directed and bycatch fisheries for sharks by different gear types often require specialized management approaches depending on the respective management objectives. Fishing gear and biological characteristics affect a species' catchability need to be considered. For example, pelagic and semi-pelagic species that swim actively in the water column are more likely to encounter a gill net or hooks and, therefore, have a higher catchability factor than demersal species with respect to those gear types/configurations. Demersal species, on the other hand, are more vulnerable to demersal trawling.

Indian Fisheries Modern Policy History

The Wildlife Authority of India is the national body governing conservation of endangered species in India through enforcement of the Indian Wild Life (Protection) Act, 1972. India's first move towards shark conservation was in 2001 when 10 species of elasmobranchs were included under Schedule I of the Indian Wildlife (Protection) Act, 1972. This was the result of rampant whale shark hunting along the north-west coast of

India, particularly in Gujarat during the latter half of the 1990s. These 10-species included four species of sharks, two species of rays, one species of guitar fish and three species of sawfishes were declared protected under Schedule I of the WPA, 1972, by the Ministry of Environment and Forests vide Order No.1-2/2001 WL1 dated 28.05.2001. Exploitation and trade of these species have been banned and declared as punishable offences.

In August 2013, the Ministry of Environment and Forests (Wildlife Division) approved a policy advisory on shark finning (vide F. No4-36/2013WL, 21 August 2013), prohibiting the removal of shark fins on board a vessel in the sea, and advocates landing of the whole shark.

India is a signatory party to IOTC Resolution 13/06/2013 which states that Oceanic whitetips are not to be retained and are to be released unharmed, to the extent practicable, when caught in association to IOTC regulated fisheries. Following the inclusion of five species of sharks and two species of manta rays in Appendix II of CITES in September 2014, India, being a signatory party, steps have been initiated by the MoE &CC (Ministry of Environment., Forests and Climate Change, India) to consider conservatory measures for fishing and trade of four of the five shark species (oceanic white tip reef shark *Carcharhinus longimanus* and the hammer-head sharks *Sphyrna lewini, S. mokarran and S. zygaena*) and both the manta rays which are currently being commercially exploited from Indian waters. The measures to be taken would be based on a "Non-detriment Finding document" (NDF) which has been prepared by CMFRI and published during the course of this research project (Zacharia et al., 2017). Until then, it was decided at the Regional Capacity-building Workshop on CITES Appendix II listing of sharks and manta rays, held at Chennai in August 2014, that trade regulations would be affected by introducing a "minimum fin size" for legal export, subject to the "no finning" policy of the Government.

In February of 2015, the Department of Commerce of the Ministry of Commerce and Industry, Govt. of India, through Notification No.110/(RE-2013)/2009-2014 inserted a new entry at Sl. No 31A in Chapter 3 of Schedule 2 of ITC (HS) (Classification of Export & Import Items), prohibiting the export of shark fins of all species of sharks covered under EXIM Code 0305 71 00, and through Notification No.111/(RE-2013)/2009-2014 amended the import policy conditions of Shark fins under ITC (HS) 0305 71 00 of Chapter 03 of ITC (HS), 2012 – Schedule – 1 (Import Policy), to the effect that import policy of the item 'Shark fins' covered under EXIM Code 0305 71 00 is changed from "free" to "prohibited." In other words, Department of Commerce of the Ministry of Commerce, Government of India issued an order prohibiting the export and import of shark fins in India as of February 2015.

This of course is a new development, and the impacts of prohibition on shark fin commerce sourced from competing interest Indian fisheries (i.e. conservation & fishing sector livelihood), regardless of whether the fins in question were "finned" or whether the shark was landed legitimately and harvested for products, as well as the fisheries proximity to the world's largest demand sector in East Asia, is little understood. Regardless, as most of these revisions are relatively recent, the status of efficacy and compliance is still unknown.

In terms of India's position in the framework of overarching administration and guidelines inherent to different levels of shark fishing oversight, from local to global, India is one of the 136-member parties of the FAO Committee on Fisheries (COFI), is 2nd on the top 20 list of "shark catching" nations, and reports data to the FAO Fishstat database. It is a member of the Indian Ocean Tuna Commission (IOTC) Regional fisheries management organization (RFMO). It was not possible to confirm whether India requires its vessels to comply with the IOTC fin-to-carcass ratio. India, as required by IOTC Resolution 05/05, reports shark catch to the IOTC. Reporting under the more detailed Resolution 10/02 has yet to be tested (Lack & Sant, 2011). In terms of voluntary adherence of regulations outlined in the International Plan of Action for the Conservation and Management of Sharks (IPOA-Sharks), India has submitted an initial shark assessment report (SAR) to act as a review of shark catches, management and knowledge of species, and policies and status of stocks in the form of a report by Kizhakudan et al. (2015) entitled "Guidance on NPAO-Sharks." India does not report species or species group information in the species breakdown of catch or relevant trade categories. It currently has no National Plan of Action for the Conservation and Management of Sharks (NPOA-sharks), the creation of which is encouraged by the COFI to outline the conditions of implementation and adherence to IPOA-Sharks.

Selecting Species for Analysis

To be expected, the main, and functionally only criteria for nominating a particular species from among the total regional elasmobranch community for study and analyses in this research was the species' existence, to some non-trivial degree, within the oceanic sector of the Indian EEZ and thus privy to some form of interaction with longline gear effort in that sector. Since there is nothing as straight forward as a standard, fully agreed-upon list of "oceanic" species for the EEZ region, it thus became quickly apparent the need to define some sort of selection heuristic for the creation of an appropriate cohort of species which would generally define the full scope of the effected community, but also not be overly populated at the expense of the value of the category itself. Accordingly, the question: "how does one actually go about determining which species fall into this category in a relevant way?", immediately followed. Over 160 species of elasmobranch have been identified within the EEZ (88 sharks, 53 rays, 19 skates; Akhilesh et al., 2014; Kizhakudan et al., 2015), and as such the winnowing down of focus to some defined sub-group was necessary from the earliest stages of experimental design and well in advance of any analytical or broadly organizational actions. This step effectively completed that outstanding perquisite, by populating in real terms the abstract and broadly theoretical assembly of organisms operating at the focus of the venture—that is, the community of sharks defined by the ecologically distinct environment of the oceanic sector of the Indian EEZ.

Limits of Ecological Description in Effective Categorization for Less Known Species

Firstly, knowledge of general habitat affiliation, as perhaps would be found in a field guide or a species encyclopedic profile, is less helpful that one may initially anticipate. Although general tropes may be known, the fine nuances of regional and life-history based mobility for many shark species is less well documented for many non-high-profile species and thus adhering only to these sources and their basic and overly categorical descriptions may be overly restrictive. Inversely, safer descriptions of territorial range of less well-known species may be overly broad, to the extent that no firm declaration may be posited about their true presence within a given sector (depth-wise or coastal vs. oceanic), especially so for species that are known to inhabit both spaces (coastal and oceanic, like some hammerheads). Fisheries dependent data of catch composition also has the ability to be misleading on this front, firstly as trades-persons may not be equipped to report on a relatively accurate species-specific basis the full community of species encountered (Chrysafi & Kuparinen, 2015), especially in terms of morphologically similar taxa or for more cryptic species that would be less commonly observed within the context of perhaps specific vessel or crew experience, and thus not recorded, yet at scale such cryptic species could be accruing a non-trivial amount of impact at a population level.

Impediments to Membership Identification for Oceanic Cohort from Fisheries Dependent Summary Data

More acutely, since the relevant fisheries management organizations which monitor national catch statistics (most notably the CMFRI, but numerous other scientific organizations and government bureaucracies are involved at various points) do not actively track elasmobranch landing to a species specific level in a significant way (at least within its publicly available, front-end assessment products) (see CMFRI Annual Reports, i.e. CMFRI, 2015; CMFRI, 2016, etc.), national catch data cannot be leveraged very usefully to cleanly define a set community of commonly landed sharks for the oceanic longline sectors. Although many auxiliary publications do indeed successfully implement species-specific observation resolution, they are to some degree more localized (Mohanraj et al., 2009 [Chennai]; Manojkumar, Zacharia, & Pavithran [Malabar

Coast, Karnataka]), which lessens the validity of mapping their findings onto a broader and more general profile of community bycatch assemblage. Furthermore, the driving organizational methodology for calculating national, summary-level, gross-catch values by the CMFRI is based around geographical scaling and counting at point of landing (Srinath, Kuriakose & Mini, 2005; Mini, 2015). Although this trope is a functional requirement at scale, and may be supremely useful on the grounds of simple operational efficacy and the determination of total values via the nearly intractable logistical prospect of total direct accounting of landings for the entire Indian subcontinent, it is, however, lacking in the capacity to make firm claims about the true point-of-catch, geographically speaking, for various taxa (this becomes relevant as at least for the domestic fleets, high mobility around the coast defines the norm as different fleets which ostensibly are based out of particular states follow stocks around the whole continent based upon the movement of seasonal abundance gradients for many taxa, and may ultimately land and offload in significantly different areas than where catch and effort was actually occurrent). This is not so much a criticism against the rigors of the driving national catch calculation methodology in achieving its stated analytical goal, but rather a specific deficiency that is magnified contextually given this study's specific data need, that is region and marine zone stratified catch information for sharks at a species-specific level. Various significant treatises have been published which conversely do adequately and comprehensively engage such difficult questions regarding summary realities of elasmobranch catch in the face of many particular and idiosyncratic fishing effort scenarios at different geographic resolutions, and thus unite a large body of adequate though disjointed understanding of sharks within the complex and dynamic system of the Indian EEZ (see Raje et al., 2002; [CMFRI] Kizhakudan et al., 2015).

Finally, the contractual basis of the international industrial long-line under the "Letter of Permission" (LOP) scheme largely waives any necessity to land Indian EEZ catch domestically (Mathew, 2003), and thus much of possible catch resolution is lost on two fronts. Firstly, the primary manner of off-loading is accomplished via transshipment at sea for these vessels, and therefore the physical catch for objective tally by domestic national fisheries agencies is nullified (Pramod, 2012; Greenpeace India, 2012). Secondly, this situation may theoretically be remedied though satisfactory log-book records and other self-policed data recording schemes. However, the history of compliance activity of these vessels can be summed up as historically quite sketchy (Pramod, 2010; Greenpeace India, 2012), and data raw data, such as it is, should be treated with appropriate caution.

Aggregation of Scientific Longline Surveys to Inform Oceanic Shark Cohort Membership

A reasonable solution was derived by turning to the body of literature on this topic in a general way; a few key instances of this having been cited above, but specifically, the development of an aggregate bycatch community profile was ultimately furnished in terms of key membership through the inter-comparison of results from a number of a scientific longline bycatch surveys specifically simulating oceanic tuna longline effort and bycatch effect within relevant regional seas. The survey results were selective via their cumulative reach across the major marine geographies of the oceanic EEZ (both coasts and A&N thoroughly represented) as well as to some degree via their temporal span, coving trends and observation beginning in the from the early 2000's to the present. The biodiversity of the catch profile has changed and broadly increased in tandem with the development of the fishery (Akhilesh et al., 2014; Kizhakudan et al., 2015). A dimension of temporal perspective is also useful for codifying the most significant and long-standing bycatch taxa. This perspective is useful regarding the defined mandate of constructing a species profile that has general applicability and is thus not couched too deeply in sub-regional or local fishing schemes or alternatively any specific fishing 'moment'. The ebb and flow of certain fixture taxa over time within the broader oceanic LL catch profile is noteworthy and may act as a lead-in to further inquiry; though, the implications of which are decidedly multi-faceted and are not necessarily due to depletion effects.

Because these efforts were necessarily competent to identify species at the point of catch in a credible manner, this list is therefore defined in empirical terms. Seven key surveys were utilized to frame key oceanic species membership. The ubiquity of certain species membership can be roughly inferred by the number of surveys they were sighted in. All considered, essentially all species brought up by all surveys were elected as the core focus group for analysis within this research, with only one or two species being eliminated as they were conceived to be highly incidental and essentially never once encountered in the literature outside the specific inclusion in the single survey, or taxa that were only defined at the genera level, likely because they were too cryptic or rare for immediate identification in the field. The seven surveys which generated the core oceanic cohort of bycatch sharks are defined in the brief table below (Table 4).

Table 4. Scientific longline surveys used to establish grouping of oceanic sharks in Indian Exclusive Economic Zone.

No.	Title of Study
1	Bhargava, A. K., Somvanshi, V. S. & Varghese, S. (2002). Pelagic sharks by-catch in the tuna longline fishery. In: N.G.K. Pillai, N. G. Menon, P.P. Pilla & U. C. Ganga (Eds.), *Management of Scombroid fisheries* (pp. 165-176). Kochi, IN: CMFRI.
2	John, M. E., & Varghese, B. C. (2009). *Decline in CPUE of oceanic sharks in the Indian EEZ: urgent need for precautionary approach* (IOTC-2009-WPEB-17). Mombasa, Kenya: Working Party on Ecosystems and Bycatch, Indian Ocean Tuna Commission
3	Sinha, M. K., Pandian, P. P., Pattanayak, S. K. and Kar, A. B. (2010). Spatio-temporal distribution, abundance and biodiversity of oceanic sharks occurring in Andaman and Nicobar waters. In: Ramakrishna, C. Raghunathan, & C. Sivaperuman (Eds.), *Recent Trends in Biodiversity of Andaman and Nicobar Islands* (pp. 373-385). Kolkata, IND: Zoological Survey of India.
4	Kar, A. B., Govindaraj, K., Prasad, G. V. A., Ramalingam, L., & Blair, P. (2011). *Bycatch in tuna-longline fishery in the Indian EEZ around Andaman and Nicobar Islands* (IOTC–2011–WPEB07–19). Victoria, SY: Working Party on Ecosystems and Bycatch, Indian Ocean Tuna Commission
5	Promjinda, S., & Chanrachkij, I. (2011). *Report on bycatch of tuna longline fishing operation Eastern Indian Ocean by SEAFDEC research vessels year 2005-2011* (IOTC-WPEB07-48). Victoria, SY: Working Party on Ecosystems and Bycatch, Indian Ocean Tuna Commission.
6	Premchand, Ramalingam, L., Tiburtius, A., Siva, A., Das, A., Sanadi, R. B. & Tailor, R. K. B. (2015). *India's National Report to the Scientific Committee of the Indian Ocean Tuna Commission, 2015* (IOTC-2015-SC18-NR09[E]). Mumbai, IND: Fisheries Survey of India.
7	Varghese, S. P., Vijayakumaran, K., Tiburtius, A. & Mhatre, V. D. (2015). Diversity, abundance and size structure of pelagic sharks caught in tuna longline survey in the Indian seas. *Indian Journal of Geo-Marine Sciences*, *44*(1), 26-36.

Table 5 provides a list of species covered in this study.

Table 5. Community of key oceanic shark species nominated for study analysis with profile information.

	Name			Fisheries Profile (Total Indian EEZ)			Instrumentation for International Mgmt.				
Sp. No. [a]	Common	Scientific	Citation	Abundance in fishery [b]	Habitat / Geography [c]	Gears [d]	IUCN Status [e]	CITES Monitored [f]	CMS Protected [g]	HMS (Y/N) [h]	Survey (s) where species present [i]
1	Scalloped hammerhead	*Sphyrna lewini*	(Griffith & Smith, 1834)	*****	Marine / brackish, pelagic-oceanic, EC & WC	Longlines, hook & line, gillnets and trawlnets	EN	Appx II	Appx II	Y	2, 4, 6, 7
2	Blue shark	*Prionace glauca*	(Linnaeus, 1758)	**	Marine, pelagic-oceanic, EC & WC	Longlines, hook & line, pelagic & bottom trawls	NT	–	Appx II	Y	1, 2, 5, 7
3	Silky shark	*Carcharhinus falciformis*	(Bilbron, 1839)	*****	Marine, reef associated, epipelagic, EC & WC	Longlines and bottom set gill nets	VU	Appx II	Appx II	Y	2, 5, 6, 7
4	Oceanic whitetip	*Carcharhinus longimanus*	(Poey, 1861)	****	Marine, pelagic-oceanic, EC & WC	Longlines	VU	Appx II	–	Y	1, 2, 3, 4, 5, 6, 7
5	Tiger shark	*Galeocerdo cuvier*	(Péron & Lesueur, 1822)	*****	Marine / brackish, benthopelagic, EC & WC	Longlines, hook & line, bottom set gill nets and bottom trawl	NT	–	–	Y	1, 2, 3, 4, 5, 6, 7
6	Dusky shark	*Carcharhinus obscurus*	(Lesueur, 1818)	****	Marine / brackish / reef associated, pelagic, EC & WC	Longlines, hook & line and bottom set gillnets	VU	–	Appx II	Y	5, 6, 7
7	Thresher shark	*Alopias vulpinus*	(Bonnaterre, 1788)	***	Marine, pelagic-oceanic, EC & WC	Longlines and drift gillnets	VU	Appx II	Appx II	Y	1, 2, 3, 4, 6, 7
8	Gulper shark	*Centrophorus granulosus*	(Block & Schneider, 1801)	***	Marine, bathydemersal, EC & WC	Bottom trawls, pelagic trawls and hook & line	DD?	–	–	N	5
9	Crocodile shark	*Pseudocarcharhias kamoharai*	(Matsubara, 1936)	*	Marine, pelagic-oceanic, WC	Pelagic & tuna longlines	NT	–	–	N	5
10	Great hammerhead	*Sphyrna mokarran*	(Rüppell, 1837)	****	Marine/brackish, pelagic-oceanic, EC & WC	Longlines, hook & line, gillnets and trawlnets	EN	Appx II	Appx II	Y	2, 4, 5, 7
11	Shortfin mako	*Isurus oxyrinchus*	(Rafinesque, 1810)	****	Marine, pelagic-oceanic, EC & WC	Gillnets, longlines and hook & line	VU	–	Appx II	Y	1, 2, 3, 4, 5, 6, 7
12	Longfin mako	*Isurus paucus*	(Guitart, 1966)	**	Marine, pelagic-oceanic, EC & WC	Gillnets, longlines and hook & line	VU	–	Appx II	Y	7
13	Pelagic thresher	*Alopias pelagicus*	(Nakamura, 1935)	****	Marine, pelagic-oceanic, EC & WC	Longlines and drift gillnets	VU	Appx II	Appx II	Y	1, 2, 3, 4, 5, 6, 7
14	Smooth hammerhead	*Sphyrna zygaena*	(Linnaeus, 1758)	****	Marine / brackish, pelagic-oceanic, EC & WC	Longlines, hook & line, gill nets and trawl nets	VU	Appx II	–	Y	2, 3, 4, 7

15	Hardnose shark	*Carcharhinus macloti*	(Müller & Henle, 1839)	****	Marine, demersal, EC & WC	Gillnets and longlines	NT	–	–	Y	1, 2, 3, 4, 6
16	Spinner shark	*Carcharhinus brevipinna*	(Müller & Henle, 1839)	****	Marine, reef associated, pelagic, EC & WC	Longlines, bottom set gill nets and hook & line	NT	–	–	Y	6
17	Bigeye Thresher	*Alopias superciliosus*	(Lowe, 1841)	****	Marine, pelagic-oceanic, EC & WC	Longlines and drift gillnets	VU	Appx II	Appx II	Y	1, 2, 3, 4, 5, 6, 7
18	Silvertip shark	*Carcharhinus albimarginatus*	(Rüppell, 1837)	***	Marine, benthopelagic, reef associated, EC & WC	Longlines and gill nets	VU	–	–	Y	1, 2, 3, 4, 6, 7
19	Whitecheek shark	*Carcharhinus dussumieri*	(Müller & Henle, 1839)	****	Marine, reef associated, mesopelagic, EC & WC	Trawl and bottomset gillnets	NT	–	–	Y	1, 2, 6, 7
20	Sharpnose sevengill	*Heptranchias perlo*	(Bonnaterre, 1788)	**	Marine, bathydemersal, EC & WC	Bottom trawls and longlines	NT	–	–	N	5
21	Grey reef shark	*Carcharhinus amblyrhynchos*	(Bleeker, 1856)	***	Marine, costal-pelagic, reef associated, EC & WC	Longlines	NT	–	–	Y	4, 5, 6, 7
22	Blacktip shark	*Carcharhinus limbatus*	(Müller & Henle, 1839)	*****	Marine / brackish, reef associated, pelagic, EC & WC	Longlines, hook & line, bottom set gill nets and bottom trawl	NT	–	–	Y	1, 2, 3, 4, 5, 6, 7
23	Milk shark	*Rhizoprionodon acutus*	(Rüppell, 1837)	*****	Marine / freshwater / brackish, benthopelagic, EC & WC	Bottom trawl, gill nets, longlines, hook & line	LC	–	–	Y	2, 3, 4
24	Spot-tail shark	*Carcharhinus sorrah*	(Müller & Henle, 1839)	*****	Marine, reef associated, coastal, EC & WC	Gillnets and longlines	NT	–	–	Y	1, 2, 3, 4, 6, 7
25	Sandbar shark	*Carcharhinus plumbeus*	(Nardo, 1827)	*	Marine / brackish, benthopelagic, EC & WC	Longline, bottom set gillnets and hook & line	VU	–	–	Y	N/A
26	Spadenose shark	*Scoliodon laticaudus*	(Müller & Henle, 1838)	*****	Marine / brackish, demersal, EC & WC	Longlines, hook & line, gill nets, traps and bottom trawl	NT	–	–	Y	2, 3, 4
27	Blacktip reef shark	*Carcharhinus melanopterus*	(Quoy & Gaimard, 1824)	*****	Marine / brackish, reef associated, demersal, EC	Gillnets and longlines	NT	–	–	Y	1, 2, 3, 4, 6
28	Zebra shark	*Stegostoma fasciatum*	(Hermann, 1783)	***	Marine / brackish, reef associated, demersal, EC & WC	Drift gillnets	EN	–	–	N	2
29	Broadfin shark	*Lamiopsis temminckii*	(Müller & Henle, 1839)	**	Marine / brackish, demersal, EC & WC	Gillnets and longlines	EN	–	–	Y	1, 2
30	Sliteye shark	*Loxodon macrorhinus*	(Müller & Henle, 1839)	***	Marine, demersal, EC & WC	Gillnets and longlines	LC	–	–	Y	6

31	Pondicherry shark	*Carcharhinus hemiodon*	(Müller & Henle, 1839)	!	Marine / brackish, demersal, EC & WC	Hook & line, bottom set gill nets and bottom trawl	CR [†]	–	–	Y	6[‡]

Note. **ICUN** = International Union for the Conservation of Nature; **DD** = Data-Deficient; **LC** = Least Concern; **NT** = Near-Threatened; **VU** = Vulnerable; **EN** = Endangered; **CR** = Critically Endangered; **CITES** = Convention on International Trade in Endangered Species of Wild Fauna and Flora; **CMS** = Convention on the Conservation of Migratory Species of Wild Animals; **UNCLOS** = United Nations Convention of the Law of the Sea; **HMS** = Highly Migratory Species; **NPOA-Shark** = National Plan of Action for Sharks; **FSI** = Fisheries Survey of India; **WC** = West Cost [of India]; **EC** = East Cost [of India]; (*****) Predominant in commercial shark landings; (****) = Common occurrence; (***) = Moderate occurrence; (**) = Rare occurrence; (*) = Isolated reports only; (!) = Protected under WPA, 1972; (?) = Needs confirmation.

[a] These species numbers, having been linked with a specific species in this formative table, will be equivalent to the same species across all tables in the study (i.e., 1 = *S. lewini*, 2 = *P. glauca*, 3 = *C. falciformis*,… , 31 = *C. hemiodon* for every table within the study) and thus forgoing the need to relabel every table with the names of the same shark species in every instance.

[b] The data in column 5 is from Guidance on National Plan of Action for Sharks in India (p. 88-98), by Kizhakudan et al., 2015, Kochi, IND: Central Marine Fisheries Research Institute. Although general in nature, it is believed to be of use within the table assembly, which attempts to encapsulate all prior assessment criteria for key species which will be privy to the full scope of analysis of this study. It should be noted that these values refer to species prevalence/abundance in the context of **the entire marine capture fishery** of the Indian EEZ, and not simply the oceanic tuna LL fishery of the Indian EEZ—albeit the latter is usually what is being referred to in terms of the scope for interpreted results of this study. These designations of occurrence within the Indian marine fishery may be misleading if a reader does not note which framing constraints are being employed.

[c,d] The values in and /or descriptions in columns 6 & 7 are taken from the same publication and figure as column 5, i.e., Kizhakudan et al. (2015) Guidance on NPOA-Sharks. CMFRI, 2015. They also apply to the entire marine capture fishery of the India EEZ, and not exclusively the oceanic tuna LL fishery of the EEZ. Otherwise, their interpretations are face value, where WC & EC refer to West Coast and East Coast of India respectively.

[e] IUCN Red List designations are up to date as of the 2017-3 iteration of the database.

[f] The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is an international agreement between governments. Its aim is to ensure that international trade in specimens of wild animals and plants does not threaten their survival. The convention works by subjecting international trade in specimens of selected species to certain controls. All import, export, re-export and introduction from the sea of species covered by the Convention must be authorized through a licensing system. Each Party to the Convention must designate one or more Management Authorities in charge of administering that licensing system and one or more Scientific Authorities to advise on the effects of trade on the status of the species. **Appendix I** includes species threatened with extinction. Trade in specimens of these species is permitted only in exceptional circumstances. **Appendix II** includes species not necessarily threatened with extinction, but in which trade must be controlled in order to avoid utilization incompatible with their survival. Within appropriate cells, species affiliation with a certain Appendix (I, II or none) is given via a clear written descriptor. If the cell is blank with a dash, then the species is not covered by the policy scope of CITIES (i.e., none).

[g] The Convention on the Conservation of Migratory Species of Wild Animals (CMS) is an environmental treaty under the aegis of the United Nations Environment Programme. CMS provides a global platform for the conservation and sustainable use of migratory animals and their habitats. CMS brings together the States through which migratory animals pass, the Range States, and lays the legal foundation for internationally coordinated conservation measures throughout a relevant species' migratory range. CMS maintains the following appendices to list and order migratory species to which the Convention applies. **Appendix I** comprises migratory species that have been assessed as being in danger of extinction throughout all or a significant portion of their range. Parties that are within

the Range of migratory species listed in Appendix I shall endeavor to strictly protect them: by prohibiting the taking of such species, with very restricted scope for exceptions; conserving and where appropriate restoring their habitats; preventing, removing or initiating obstacles to their migration and controlling other factors that might endanger them. **Appendix II** covers migratory species that have an unfavorable conservation status and that require international agreements for their conservation and management, as well as all those that have a conservation status which would significantly benefit from the international cooperation that could be achieved by an international agreement. The Convention encourages the Range States to place species listed on Appendix II to conclude global or regional Agreements for the conservation and management of individual species or groups of related species. Within appropriate cells, species affiliation with a certain category of Appendix (I, II, or none) is given via a clear written designation. If the cell is blank with a dash, then the species is not covered under the policy scope of CMS (i.e. none).

[h] The United Nations Convention of the Law of the Sea—**Annex I** (UNCLOS-Annex I) defines species that are designated as Highly Migratory Species (HMS). This designation eschews special legal relevance within parties to the convention (i.e. have a specific legal relevance above a biological one in some cases), as species with these designations are defined to exist between and across territorial claims and thus shall be managed as a transboundary stock. UNCLOS-Annex I expressly lists species that are privy to the official designation as a Highly Migratory Species. Within appropriate cells, species designated as an HMS via express inclusion within UNCLOS-Annex I are designated as such with a yes or no (Y/N).

[i] Numbers correspond to a certain citation, the list of which publications linked to specific numbers used can be found in the previous Table 4, e.g. 1 = [Bhargava et al., 2002]; 2 = [John & Varghese, 2009]; etc.

[†] Possibly extinct; last seen in wild 1979. [‡] **N.B.** 3 specimens of *C. hemiodon* were cited as having been captured in 2011 in a survey conducted by the Fishery Survey of India (FSI), the explicit data account of which was couched within a report to the IOTC Working Party on Tropical Tunas (WPTT). Of note is that not even a sentence of discussion was given to this important observation, as the species has not been successfully sighted in the wild (living or dead?) in several decades. These considerations evaluated together raise the possibility that entries/specimen recordings of *C. hemiodon* could possibly be the byproduct of a clerical error, field misidentification, or alternatively, since the data included within the report was 3 years old, it may have been covered with sufficient fanfare when it was temporally relevant and originally published. Presently, however, it is very hard to verify the credibility of this line of evidence. Such as it is, this is also the first instance that an observation of *C. hemiodon* has been made or recorded anywhere in the new millennium (at least to the knowledge of the author), and given the importance of the claim, it should be further clarified and investigated. The report in which the observation of *C. hemiodon* was listed is the following: Premchand, Ramalingam, L., Tiburtius, A., Siva, A., Das, A., Sanadi, R. B. & Tailor, R. K. B. (2015). *India's National Report to the Scientific Committee of the Indian Ocean tuna Commission,* 2015 (IOTC-2015-SC18-NR09[E]). Mumbai, IND: Fisheries Survey of India.

Research Questions, Hypotheses and Specific Aims

The following list comprises the key research questions I addressed over the course of this investigation:

1. What is the history and contemporary state of the overall shark harvest in India; furnished via a holistic review of the current state of knowledge?
2. How is the shark harvest framed in terms of regional characteristics, capacity, history as well as present day social and cultural demography? [Regional character having been flagged as a high-importance lens for critical consideration and effective understanding]
3. What are the values (both yearly and overall mean) of fishing mortality (F), as well as appropriate uncertainty ranges, stemming from longline bycatch for relevant shark species/stocks extant in the oceanic sector of the Indian EEZ?
4. What are the values of defined biologically based management reference points (i.e. F_{msm}, F_{lim}, F_{crash}), as well as appropriate uncertainty ranges, for relevant shark species/stocks extant in the oceanic sector of the Indian EEZ?
5. On a species-specific basis, what is the stock status determination in terms of absolute relationship to sustainable-level mortality for relevant shark species/stocks extant in the oceanic sector of the Indian EEZ, expressed in a way that may be easily interpreted by policy makers (i.e. Low-Risk, Precautionary Medium-Risk, Medium-Risk, Precautionary High-Risk, High-Risk, Precautionary Extreme High-Risk, Extreme High Risk)?

Hypothesis

With respect to the prior research questions, the primary hypothesis I examined posits that the bycatch/byproduct component of the longline fishery of the oceanic sector of India’s Exclusive Economic Zone is incurring unsustainable fishing mortality pressure (F) on its community of constituent, pelagic (oceanic) shark species. Therefore, a fishing mortality model has been proposed to address this claim, the claim being explicitly: The community of shark species/stocks extant within the oceanic sector of the Indian EEZ are incurring unsustainable levels of fishing mortality through bycatch in longline gear.

“Unsustainable” is defined here as a rate at which marginal replacement is non-zero and negative, the mathematical end-state being that at some future time t the stock/population will crash (i.e. experience local extinction or extirpation), within a defined geographical range—that range being the oceanic sector of the Indian Exclusive Economic Zone. The output of a model in which this hypothesis is addressed should furnish a quantitatively defined of indicator of stock status. Additionally, it should operate within the commonly held notions of robustness expected within the fields of fisheries and conservation sciences for the delivery of such claims. In this regard robust quantification of the levels of uncertainty should also be furnished.

Specific Aims

The hypothesis articulated above generates specific research aims and associated strategies of analysis. In accomplishing these specific aims, the foundational requirements are met to furnish the analyses necessary to address the hypothesis and fulfill the more expansive research questions previously enumerated.

1. Given the multi-species, multi-gear and generally complex nature of the total marine fishery in India, define the relevant subsector, both with minimal convolution and possible significant impact on sharks, which may be assessed sufficiently given the knowledge and available data.
2. Determine a tractable method for species specific stock assessment for data-limited fisheries that can negotiate all relevant and regionally specific data paucities extant in said specified fishery.
3. Investigate the analytical options that are available to merge multiple data-sets and disparate data-types into to single framework and additionally may express relevant statistical uncertainty about data.
4. Establish using appropriate criteria the grouping of species which comprises the community of sharks resident in the oceanic sector of the Indian EEZ.
5. Define the target species of the longline fishery in the oceanic sector of the Indian EEZ.
6. Delimit the precise geographical/areal limits and size of the Indian Ocean Tuna Commission (IOTC) managed area (i.e. IOTC competence area).
7. Delimit the precise geographical/areal limits and size of the oceanic sector of the Indian EEZ, i.e., the operative Fishery Jurisdiction Area (FJA).
8. Available to an annual resolution, establish the geographical/areal limits and location of longline effort in the oceanic sector of the Indian EEZ (i.e., $A_{i,f}$).
9. Establish the geographical/areal limits and size of core habitat of both target species (specifically Yellowfin tuna) and bycatch sharks in the oceanic sector of the Indian EEZ (i.e., $A_{i,J}$).

10. Quantify the yearly catch (C) in tonnes of target species (specifically Yellowfin tuna) by longline gear in the oceanic sector of the Indian EEZ.
11. Quantify the yearly catch (C) in tonnes of target species (specifically Yellowfin tuna) for all gears combined in the IOTC competence area.
12. Quantify the yearly values for fishing mortality (F) for target species (specifically Yellowfin tuna) by longline within the oceanic sector of the Indian EEZ.
13. Quantify the yearly values for fishing mortality (F) for target species (specifically Yellowfin tuna) for all gears combined within the IOTC competence area.
14. Quantify the values of habitat based Encounterability (q_i^h), size-dependent Selectivity (q_i^λ), and Post-Capture Mortality (PcM_i) for target species (specifically Yellowfin tuna) as well as for all relevant, individual shark bycatch species.
15. Quantify the values of core life history (vital) parameters of relevant, individual shark bycatch species (r, λ, $\hat{w}$, M_{pub}, K, L_{max}, L_∞, T (°C), t_{max}, t_{mat}, L_{mat}, L_0, t_0, ω) [see Table 13, Chapter IV for parameter definitions].
16. Quantify the values of natural mortality (M) for relevant, individual shark bycatch species, provided by various M Estimator functions.

Chapter II

Methods, Part I: Pre-model Operations & Data Acquisition

Conceptually speaking, this study is a form of metanalysis. As such, it relied explicitly on the legacy of fisheries' data assets inherited by the assessor and attempted to combine and analyze them in a novel way (Figure 7). Given this nature, the methodology of this study was designed to facilitate an analytical process to derive intended outputs.

Figure 7. Skiff. Small boats shuttling catch from larger craft into Kasimedu fishing harbor for wholesale, just after sunrise (photo by author, Chennai. 2016).

The analytical methods were selected based on two criteria: 1) the actionable overlap in data profiles necessary to calculate a result via the method's proprietary data requirements/constraints vs. those data resources actually available for the fishery; and 2) the aforementioned analytical method's mathematical capacity to weave together various data-streams into a single statistical framework.

Regarding the first criterion, the study garnered a significant part of its theoretical basis from the work of Shijie Zhou and his colleagues' SAFE longline equations (Zhou et al., 2007, 2009, 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012; see also Zhou & Griffiths, 2008; Zhou, Yin, et al., 2012). The SAFE equations provide a viable assessment strategy for the data-limited determination of longline bycatch mortality, which furthermore also utilizes as initial inputs values from a variety of data-streams that were actually available within the corpus of data/knowledge accumulated in relation to our fishery of interest. However, this study does not simply reapply or recycle the methods and analyses performed in prior research utilizing SAFE schemes (not that there is anything intrinsically negative about that approach), but it additionally innovates with respect Zhou's SAFE LL equations, particularly the most recent iterations/refinements of the equations (viz., Zhou et al., 2011; Zhou & Fuller, 2011; and Zhou, Fuller & Daily, 2012). I revised the analytical program's core mathematical architecture, such that relevant deterministic principles outlined via the work of Zhou and various collaborators (in publications just previously listed) were couched within an overtly stochastic interpretation of features (or variables/parameters) operating within the assessment model (or SAFE LL formula). By solving the Zhou et al. SAFE longline equation so all realistically uncertain variables were considered stochastic (and not simply the output of formulaically linked values assumed to be completely accurate recapitulations of known, discrete natural relationships furnished deterministically), the overall level of uncertainty for the outputs could be quantitively rendered. That is, cumulative uncertainty drawn appropriately from all independently and/or conditionally contributing sources within the model would be manifest in the Credible Value range of the core outputs, and thus produce scientifically robust determinations which adequately acknowledge the inherent uncertainties of the data-limited fisheries assessment environment under consideration. Consolidation of prior information and different data sets into a single statistical "test" was available within the context of Bayesian statistical inference, and ultimately solved by the process of Monte Carlo Markov Chain simulation. Thus, criterion 2 was met in this fashion.

Methodology Structure in Brief: A Three-Part Organization

Organizationally speaking, the methodology of this venture falls into three main phases/arcs/parts, which will be covered in Chapters II, III and IV as follows:

- Part I: Pre-Model Operations & Data Acquisition [Ch. II]
- Part II: Bayesian Hierarchical Model for the Derivation of Species-Specific Instantaneous Fishing Mortality (F) [Ch. III]
- Part III: Bayesian Hierarchical Model for the Derivation of Species-Specific Biological Reference Points (F_{msm}, F_{lim}, F_{crash}) for Management [Ch. IV]

Broadly defined, Part I ("Pre-Model/Pre-Analysis Operations") consisted of gathering, transforming, and generally arranging data (or component values), novel derivation of component values (in circumstances they have never been published though applicable strategies are available), and in a few instances designing novel formulae for the derivation of novel component values (when specific data have never been published and are additionally intractable to standard forms of derivation, usually due to specific data needs). Additionally, a variety of pre-model values were garnered in this section, which were utilized as data in forthcoming Bayesian Hierarchical Models outlined in their respective chapters (for a summary listing of all relevant values acquired in Part I, see Tables 8 & 9 [at end of chapter]).

Relegated to Chapters III and IV respectively, Methods Parts II & III catalogue the main analytical features of the study. Using specified Bayesian Hierarchical models, mean values as well as the quantification of uncertainty through Credible Intervals (C_RI) were produced, correspondingly, for one of two important unknown variables (parameter)—(F) and $\{F_{msm}, F_{lim}, F_{crash}\}$. In the final maneuver of the analysis, these important values were ultimately brought together and compared in a specified framework, the output of which is a final analytical determination that may directly be interpreted as stock status designations of experienced fishing risk on a per-species level.

Detailed Component Overview for Central Fisheries Equation: Zhou's Longline Bycatch Mortality Equation for Data-Poor Non-Target Species

Equation (1) or "Zhou's LL equation" (or some permutation thereof, i.e. the shorthand name that will be used frequently throughout the remainder of this study to refer to the equations and corresponding concepts described subsequently) and its primary sub-equation ρ (Equation 2) are listed below. The primary Zhou et al. LL equation is further broken down by variable/parameter in the following paragraphs to give an adequate conceptual explanation of each. The total methodological scheme of this study is built substantially on the core relationship among the variables, terms, and parameters in Zhou's LL equations. Hence, basic familiarity with these variables' definitions and identities, as well as the basic algebraic relationships among these is required.

Overall SAFE Long-Line Equation (the Zhou et al. LL Equation)

Within this study, the following equation (1) is the "overall" equation used for deriving the annual instantaneous fishing mortality rate (F_i^T) for bycatch (i.e. shark) species (i) in year (T) within a data-limited longline fishery, as designed by Zhou and collaborators (Zhou et al. 2007, 2009, 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012; see primarily: 2011, 2011, 2012). Note that fishing morality is also frequently denoted as simply F (or perhaps F_i) within this study when the concept is referenced generally, or F^{ShK} or F^{YFT} to specify fishing mortality for a shark species (or multiple species) and yellowfin tuna (YFT) respectively for added contextual clarity.

$$F_{\mathrm{i}}^{\mathrm{T}} = \frac{A_{\mathrm{i,f}}^{\mathrm{T}}}{A_{\mathrm{i,J}}} q_{\mathrm{i}}^{\mathrm{h}} q_{\mathrm{i}}^{\lambda} \rho^{\mathrm{T}} (PcM_{\mathrm{i}}) \tag{1}$$

where (*i*) is the *i^th^* bycatch species.

While many standard types of stock analysis tend to utilize detailed, multi-year time-series catch data in conjunction with fleet effort to estimate relative catch rates (CPUE), in the absence of such data (which itself is not always a fully reliable data-stream and privy to a variety inadequacies [Harley, Myers, & Dunn, 2001]), the spatial overlap of the fishery / fishing effort with species habitat within the Fishery Jurisdiction

Area (FJA) is used as a proxy for likely stock impact, where unknown bycatch species' impact (specifically, fishing mortality) is linked to (better) known catch- and mortality-rates of target species (such as yellowfin tuna) or suite of target species via the correction factor ρ. Simply, the quantitative similarities of the bycatch catch-profile to the catch-profile of the target-species in the overlapping area of fishing effort (sum of values [0 to1] per 0.5° Lat. × 0.5° Long. grid w/in FJA) and species habitat distribution (quantified as occurrence probability values [0 to1] per 0.5° Lat. × 0.5° Long. grid unit w/in FJA) may be accepted as a feasible estimate of fishing mortality rate of the relevant bycatch stock. This method is a way by which quantifications of impact may be obtained in a data-poor scenario, and it is therefore defined as a highly relevant match to this study's driving design requirements.

Correction Factor (ρ^T)

Within the overall Zhou et al. LL equation given above, the term ρ (or given as ρ^T here to clarify ρ in year (T)) is known as the Correction Factor (Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012). Variable ρ is itself a relationship of other terms, and that relationship is expressed by equation (2) below. As the equation which ρ represents is itself nested within the overall Zhou et al. LL equation (1), it may additionally be referred to as the "primary sub-equation." Note well—in contrast to the overall Zhou et al. LL equation, the (i) in the ρ sub-equation refers to a specific *target species* (i), whereas the former refers to specific *bycatch species* (i.e. shark species) (i). It is important to take stock of this distinction.

$$\rho^{\mathrm{T}} = \frac{1}{n}\sum_{i=1}^{n}\frac{F_{\mathrm{i}}^{\mathrm{T}} A_{\mathrm{i,J}}}{q_{\mathrm{i}}^{\mathrm{h}}\, q_{\mathrm{i}}^{\lambda}\, A_{\mathrm{i,f}}^{\mathrm{T}}} \tag{2}$$

where (i) is the i^{th} target species.

Acting as a notational stand-in for the broader ρ sub-equation, this parameter (ρ^{T}) can be considered as a correction factor for the combination of affected area (due to bait odor dispersion and fish movement), probability of responding to bait, probability of encountering the hooks, gear efficiency after encountering, etc. Many of the terms included in the ρ sub-equation are similar to those in the overall LL equation (1); however, in the ρ sub-equation the terms refer to those associated with target species, rather than bycatch species, albeit mathematically and conceptually speaking, they are derived identically. Although in the generalized construction of the ρ sub-equation (which is given above as equation 2), multiple target species are averaged arithmetically to produces a composite ρ value; however, due to the nature of the fishery in question, only one target species of consequence was identified, which is Yellowfin tuna (*Thunnus albacares*). Some cosmetic notational changes may therefore be applied when giving the full value of ρ in the future, as in the case of this study it will only pertain to one target species as opposed to a collection; however, conceptual homologies are of course retained identically and rendered unaffected.

Fisheries Jurisdiction Area (FJA)

In real terms, the FJA is any geographic construct that controls the activity of fishing effort through any combination of a variety of control mechanics; it takes the form of a defined geographical area (Figures 8 & 9) (For Indian FJA, see Figure 15b).

This value is a constant that is defined once at the outset, though, if the

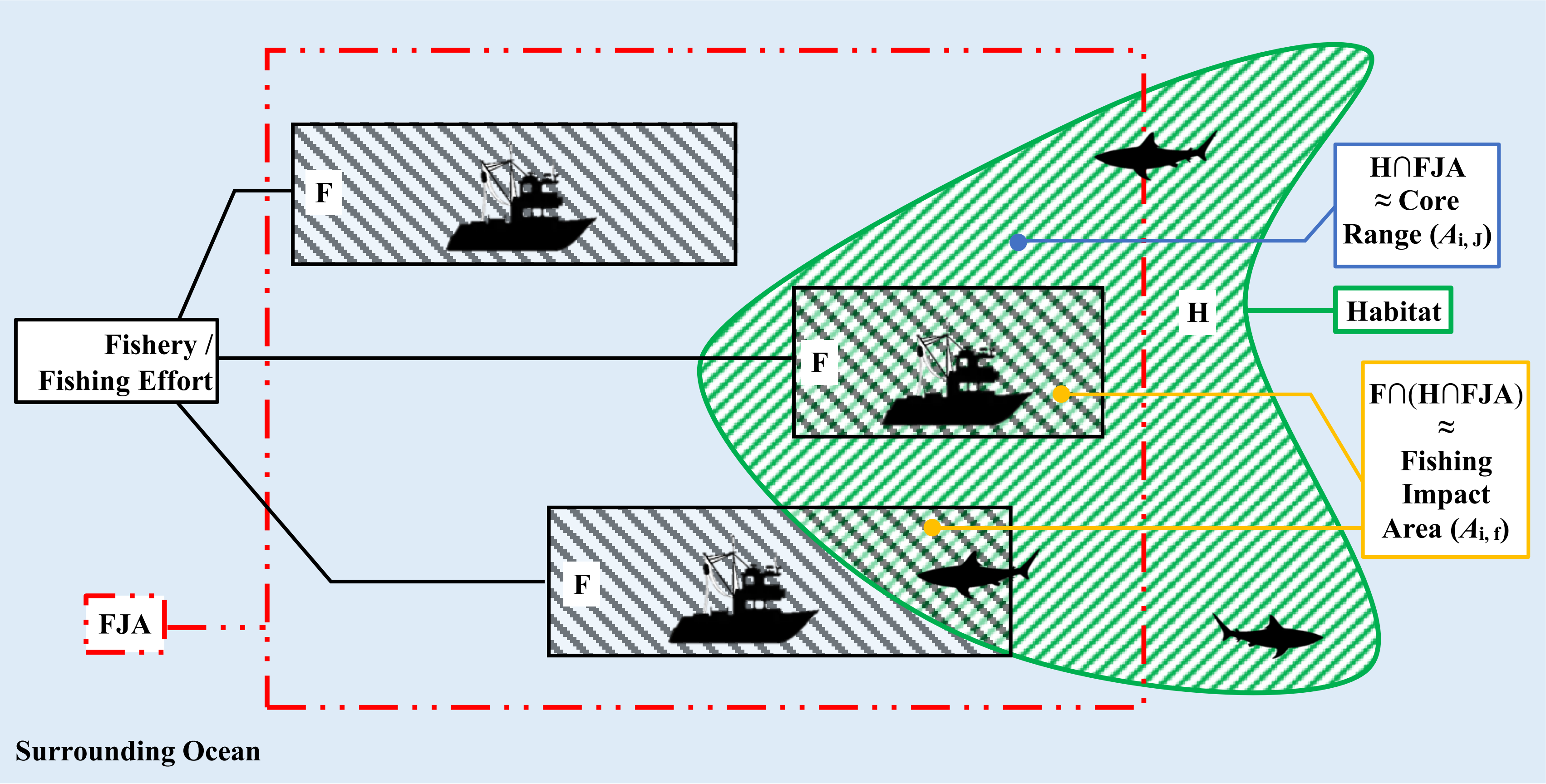


Figure 8. Graphic representation of key area relationships in Zhou et al. SAFE LL equation. Diagram of a hypothetical species' habitat, fishery jurisdiction, and fishing effort distribution. FJA = Fishery Jurisdiction Area; H = species distribution (habitat may be used); F = fished (LL station) area. H∩FJA or the overlap between Habitat and FJA is equal to Core Range ($A_{i, J}$). F∩(H∩FJA) or the overlap between area receiving fishing effort and species core distribution is equal to Fishing Impact Area ($A_{i,f}$), and is a key variable for estimating impact on bycatch species.

geographical boundary of the waters were modified (perhaps from say a management recalibration), then so necessarily would the boundaries of the FJA. Fishing Jurisdictional Areas—when the boundary lines thereof are not expressly shaped by real ecotones or intractable ecological boundaries (e.g., a coastline [marine vs. terrestrial boundary])—are essentially "imaginary" or artificial geographical constructs, which usually a government or a government permitted regulatory body chooses to acknowledge for a specific reason. In essence, a fishing jurisdictional area is simultaneously both an abstract, arbitrary spatial constraint, as well as, in real mathematical terms, the rendered polygon which defines the regulatory or otherwise self-contained area in which a fishery is permitted to operate. In our case, the FJA is used to frame the geographical extent of our fisheries model's universe or system. Anything outside this area cannot be incorporated or interact, and for all intents and purposes is considered irrelevant, even though in the real world this may not always strictly be the case. Once calculated, the numerical value of the FJA area in its raw form is used in conjunction with the subsequent two variables ($A_{i,f}$ and $A_{i,J}$) which are outlined in immediately following paragraphs.

The boundary of the FJA operational within this study is aerially defined as the number of 0.5° Lat. × 0.5° Long. grids (converted for final publication to km^2) within the overarching Indian EEZ maritime boundary, but exclusively the oceanic region, defined to the best categorical resolution feasible (Figure 9). Within this study, the oceanic region of Indian EEZ is defined as the sub-division of the Indian EEZ area (both encircling the continental mainland as well as the EEZ area of the Indian archipelagic territories of the Andaman & Nicobar Islands) that is beyond the obvious submarine,

$$\underbrace{\underbrace{\left(\text{Area}^{\text{Species Distribution}} \bigcap \text{Area}^{\text{Fishery Jurisdiction}}\right)}_{\substack{n_{\text{cells}}\ (0.5^\circ \text{ Lat} \times 0.5^\circ \text{ Long}) \\ \text{fulfillig condition of} \\ \text{intersection b/w sets}}\ =\ \text{Core Range } (A_{i,j})} \bigcap \text{Area}_{t}^{\text{Fishing Effort Dist}}}_{\substack{n_{\text{cells}}\ (0.5^\circ \text{ Lat} \times 0.5^\circ \text{ Long}) \\ \text{fulfillig condition of} \\ \text{intersection b/w sets}}\ =\ \text{Fishing Impact Area } (A_{i,f})}$$

Figure 9. Formulaic representation of key area relationships in Zhou et al. SAFE LL equation. Represents the bare minimum spatial data-dimensions required for inter-comparison and ultimate execution of the SAFE LL analysis as prescribed by the authors (Zhou, etc.); however, others may be introduced. Such as it is, the occurrence probability layer is not introduced in Figures 8 or 9, as it is just a modification (through detail addition) to the Habitat (H) layer (or species distribution). The mathematical integration of occurrence probability within this specific study analysis and how this decision deviates from the Zhou et al. (2011) model is outlined later in this chapter.

geological contour of continental shelf drop-off. This drop-off threshold is roughly equivalent to the area past 200 m depth and/or greater than approx. 50-75 km from shore (the area of NW India has a rather long continental jut). (See Figure 15b for an example of how the FJA, i.e. the oceanic zone of the EEZ, differs geographically with the standard boundary of the EEZ in Figure 15a). Because of geometrical remainders when using a grid system to model the area bounded by curves, accuracy at the boundary was improved by letting the grids partially overlapping the FJA boundary delineation take one of three possible values less than one: 0.25, 0.50 and 0.75. These values correspond to the number of quartiles included within the boundary and shape of their arrangement that best mimics the direction and proportion of the bisecting boundary line.

Core Range ($A_{\mathrm{i,\,J}}$)

The variable $A_{\mathrm{i,\,J}}$ represents total distribution area for species (i) within the fishery jurisdiction area (Figure 8). Where Habitat (H) may comprise the total range of a species across their extant distribution, core range (or core habitat) refers only to the habitat/distribution area that falls within the Fisheries Jurisdiction Area. The value of $A_{i,J}$ is equal to the sum of all values within all eligible cells, where eligible cells are defined as the 0.5° Lat. × 0.5° Long. grids where FJA and habitat distribution overlap (Figures 8 & 9). (For an example of relevant shark species core range, see Figure 14).

Cell values for habitat distribution are lifted directly from occurrence probability derivation and more generally FishBase /AquaMaps range maps for a specific species ([AquaMaps.org] Kaschner et al., 2016; [FishBase.org] Froese & Pauly, 2018). In a given eligible cell, the cell values for occurrence probability [0-1] are multiplied by the cell value for FJA area to give the final value for an eligible cell, the sum of the final values over all eligible cells equals $A_{i,J}$. The grid-based values produced as a baseline by the Aquamap.org algorithm define a metric known as Occurrence Probability. For any given species, as a geographic unit and its suite of environmental characteristics diverge from the defined "most-preferred"/optimal environmental envelope across a species' plausible range, the occurrence probability is lowered commensurately over a total possible value range of [0-1]. This results in a data product akin to a habitat distribution *gradient*, as opposed to a purely binary distribution polygon (the latter defined by the total possible area the species is known to exist, with equal likelihood at all points). Furthermore, the gradient of occurrence probability over total plausible range should likely act as rough proxy for species density phenomenon. The equation of the specific environmental envelope and its component variables used to produce per-cell occurrence probabilities are defined respectively in the Species Native Range Distribution Layer (L_1) section below. The values and computation of per-cell occurrence values are fully derived and made deliverable via the native AquaMaps algorithm & its graphical generation capabilities.

Fishing Impact Area ($A_{\mathrm{i,\,f}}$)

The term $A_{\mathrm{i,\,f}}$ (or given here as $A_{i,f}^{T}$ to denote distinct value for year (T)) is quantified as the total area (30’ [or 0.5°] Latitude × 30’ [or 0.5°] Longitude) within species i’s distributional area (i.e. grids containing non-zero species occurrence probability within FJA boundary) which also experiences longline fishing activity. This is recorded during a defined during period of interest, usually 1-year (Figures 8 & 9). (For Indian Fishing Impact Area by year, see Figures 18a–e).

Restated, $A_{\mathrm{i,\,f}}$ is equal to the sum total of per-grid values derived at each overlapping grid unit containing both oceanic longline station points and some non-zero species occurrence probability of species range distribution within the FJA. Where there was overlap, a final per grid value was derived, equal to the product of species’ occurrence probability [value 0–1] times grid-wise fishing station coverage [value: 0.25, 0.5, 0.75, 1.0]. The summation of all final per-grid values for all applicable grids (cells), each being equal to the product of the two latter values, produced a final, single and species-specific value for $A_{\mathrm{i,f}}$. This value was calculated for all 31 shark species and every target species (1 in total: Yellowfin Tuna) individually with respect to an individual year [2010–2014], as the distribution and associated per-grid occurrence probability for each species is unique and fishing station locations are obviously different each year. The areal extent of LL yellowfin tuna fishing stations was derived from a collection of annual reports from 2010–2014 presented by the Fisheries Survey of India to the IOTC Working Group on Tropical Tunas (WGTT). The reports are retrospective 1 year, ergo 2015 evaluates final data of 2014, etc. I was able to construct a tabular list of values containing the Lat. × Long. location data of the fishing stations over those years using scale map graphics included in the Indian IOTC WGTT reports (Vijayakumaran & Varghese, 2011[IOTC-2011-SC14]; Vijayakumaran & Varghese, 2012 [IOTC-2012-SC15]; Premchand, Sajeevan, & Tiburtius, 2013 [IOTC-2013-SC16-NR09]; Premchand, Sajeevan, Tiburtius, Sanadi, & Tailor, 2014 [IOTC-2014-SC17-NR09]; Premchand et al., 2015 [IOTC-2015-SC18-NR09]). (See Figure 16 for example of graphic). The specific process by which these data points were extracted from published map graphics in addition to this study's proprietary, rule-based, per-cell value attribution scheme (as well as other miscellanea) is accounted for in the relevant subsequent section titled Values for Longline Effort Distribution Layer (L_3) (see also Figure 17).

Availability

This ratio between the two areas is the fraction of species spatial distribution overlapping with the geography of known LL effort within the fishery. Where (*i*) is the *ith* bycatch shark species, availability is defined as: $A^{\mathrm{T}}_{\mathrm{i,f}}/A_{\mathrm{i,J}}$.

In my modification of the determination of $A_{i,f}$ and $A_{i,J}$ (and thus this ratio), the per-cell values are weighted by mean species Occurrence Probability, which results in an increased value for fishing activity carried out over prime habitat geography and a decreased value for a geographically equivalent effort distribution conducted over fringe habitat.

Habitat-Dependent Encounterability (q_i^h)

This variable—encounterability—is the first of three sequential components of a categorical submanifold within the overall Zhou et al. LL equation defined cumulatively as the "Catch Mechanism" variables. Broadly speaking, the product of these three components are unique, as they define value based "catch profile" symmetry between target species (in this case YFT) and potential, individual bycatch species (in our case 31 different species of sharks), with respect to the three major defining features which control proximate fishing effort mortality outcome: gear encounter (encounterability [q_i^h]), nature of gear interaction or catch process (selectivity [q_i^λ]), and mortality outcome of catch (post-capture mortality [PcM_i]).

Essentially, should a bycatch species evince an identical value to that of a target species (the latter usually defined as having a value of simply 1) as derived from the product of these three variables, from the view-point of the gear, the two organisms are effectively identical, with identical criteria to be targeted and removed by the gear. When not expressly published in the literature, the values for these three variables are allocated, at least initially, through semi-quantitative risk designations [LOW, MEDIUM, HIGH]. This is the way they are prescribed via classic Ecological Risk Assessment (ERA) analysis (Hobday et al., 2007). However, Zhou et al. (2011) and others utilize a simple conversion scheme to transform these values from the qualitative designations of [LOW, MEDIUM, HIGH] risk as garnered from Level 2 ERA analysis [Productivity & Susceptibility analysis (PSA)] (Walker, 2005; Daley et al., 2007; Murua et al., 2012) into appropriate, discrete scale values within the range [0-1]. Specifically, values were set to 0.33, 0.66, and 1.0 for species with low-, medium-, and high-risk scores, respectively.

The process by which ERA (Ecological Risk Assessment) defines the allocation of these values is outlined in a following section: "Deriving the Values for Encounterability (q_i^h)". Additional modifications to this basic scheme were utilized and the details of which may also be found in the aforementioned section. Most species' values utilized for this variable were originally derived and published as a rote data-set within Murua et al., 2012 [IOTC-2012-WPEB08-31 Rev_2]; when not defined in that study, novel values where derived as part of the body of "Pre-Analysis Operations" within the present study.

Size- and Behavior-Dependent Selectivity (q_i^λ)

This variable is defined as the second of three sequential components within the Catch Mechanisms sub-manifold, defined cumulatively as the "Catch Mechanism." The strategy used by Zhou et al. (2011) eliminates most of the less informative considerations and instead assigns values simply based on average length at maturity: [0.33] for fish <10 cm or >500 cm; [0.67] for fish between 10 and 20 cm and between 400 and 500 cm; and lastly [1.0] for fish between 20 and 400 cm (Daley et al., 2007). As with q_i^h, many utilized species' values for this variable were originally derived and published as a data-set within Murua et al., 2012 [IOTC-2012-WPEB08-31 Rev_2]; when not defined in that study, novel values where derived as part of the body of "Pre-Analysis Operations" within the present study.

Post-Capture Mortality (PcM_i)

Again, mirroring Zhou et al. (2011), the values of 0.33, 0.67 and 1.0 were given for species that have low, medium, and high probability of mortality respectively after capture and return to the water, like other studies (Daley et al., 2007; Walker, 2005a; Murua et al., 2012). The variable of Post-Capture mortality is simply (1 - Post Capture Survival). Similarly, as with q_i^{λ} q_i^{h}, many utilized species' values for this variable were originally derived and published as a rote data-set within Murua et al., 2012 [IOTC-2012-WPEB08-31 Rev_2]; when not defined in that study, novel values where derived as part of the body of "Pre-model Operations" within the present study.

Pre-Analysis Operations, Part I: Deriving Encounterability(q_i^{h}), Selectivity (q_i^{λ}), and Post-Capture Mortality (PcM_i) Initial Values for Unpublished Species

The aforementioned variables q_i^{h} and q_i^{λ} and PcM_i are central components of the previously overviewed "Zhou et al. LL" foundational fishing mortality (F_i) equation and represent the factors of Encounterability, Selectivity, and Post-Capture Mortality, respectively. Together, these three parameters comprise the three operative components of the "Catch Mechanism" submanifold of the broader fishing mortality equation; they are defined as given:

- Encounterability—defined as the likelihood that a species will encounter fishing gear deployed within its range.
- Selectivity—a measure of the likelihood that the species will be caught by the gear provided that they are encountered. Although factors affecting selectivity are necessarily gear- and species-dependent, body size in relation to gear size is perhaps the most significant driver for this aspect.
- Post-Capture Morality—a measure of the mortality probability for a species, or the proportion of members of a species that die, as a result of interaction with the

gear. Retained organisms would be receive a value of 1; however, species that are discarded alive or slip the gear may or may not survive.

The aforementioned longline fishing impact equation of Zhou et al. (2011), which is a gear specific permutation of the SAFE method, as well as the number of other cited studies which utilize these “catch mechanism” variables, are conceptually linked to the progenitor fisheries assessment methodology of Ecological Risk Assessment [for the Effects of Fishing], which is usually shortened to ERA or ERAEF (Hobday et al., 2007; Daley, 2007).

Ecological Risk Assessment: Introduction and Methodological Relevance in the Calculation of Catch Mechanism Variables

A brief primer on the evaluation scheme known as Ecological Risk Assessment (ERA), its methodology, and how it provides much of the substantive, conceptual foundation for this study’s present analysis is useful. In specific terms, the broader Ecological Risk Assessment methodology is a key prerequisite to the understanding of the “catchability mechanism” variables and the manner by which they are formally derived. In other words, to explain how values for the “catchability mechanisms” were derived when not directly available within the literature, it is first necessary to explain how they are relevant and additionally how they are derived within the context of the ERA workstream.

Codified as one of the major operative fisheries assessment typologies of the Australian Government Fisheries Management Authority over the last decade (Smith et al., 2007; Scandol, Ives, & Lockett, 2009; Arrizabalaga et al., 2011; Hobday et al., 2011), ERA has seen wide and varied application specifically in relation to elasmobranch conservation and management (Cortés et al., 2010; Murua et al., 2012; Gallagher, Kyne, & Hammerschlag, 2012). This is likely due to a key design strength which incorporates a hierarchy of analysis options, and thus facilitates the production of credible outputs along a gradient of data-availability; outputs build from qualitative, to semi-quantitative, to fully-quantitative in nature as hierarchical assessment levels are ascended.

The ERA is hierarchically broken up into three stages of analysis that undergird each other both conceptually and informationally and ultimately build towards an optimally refined and data buttressed assessment, usually in relation a particular ecosystem subcomponent (in our case a specific clade of bycatch within the fishery ecosystem effected by longline effort).

The stages are as follows: Level 1 analysis (SICA – Scale Intensity Consequence Analysis; i.e., categorization); an empirically based Level 2 analysis (PSA – Productivity Susceptibility Analysis); and a fully quantitative model-based Level 3. The methodology known as Sustainability Assessment for Fishing Effects (SAFE)—that is, the methodology on which this project's core analyses are built (i.e. the framework by Zhou et al., 2007, 2009, 2011; Zhou & Griffiths, 2008; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012)—is a specialized post-level 2 offshoot of the ERA; however, it is an offshoot specifically adapted to scaffold in fully quantitative terms fishing effects in data-limited (as well as multi-gear and multi-species) fisheries, which has been defined as a methodological prerequisite given predominant data-availability trends for the oceanic longline sector of the Indian EEZ.

This detailed description of the ERA workflow builds towards the following point: q_i^h, q_i^λ and PcM_i ,as they exist in the present SAFE methods, are literally equivalent constructs carried over from a prior, lower-tier ERA assessment, specifically a Level 2 (PSA– Productivity Susceptibility Analysis). This continuity in constructs could in theory allow for direct migration of values from the lower-level assessment to a present SAFE model.

A preliminary derivation of catch mechanism values for all three parameters was necessary for various downstream calculations within the study; however, since this study was not as a part of a broader ERA arc of ascending assessments (which was the case in Zhou et al., 2007, 2009, 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012), and therefore not having derived these values a priori, I was therefore tasked with deriving these values from 'scratch', on an as needed, per-species basis. This was required when for a particular species, there were no previously derived values of these variables extant within the literature; however, should the inverse be true, simply migrating published values into the relevant suite of dependent equations was completely sufficient and was carried out in many situations.

Encounterability (q_i^{h}) Selectivity (q_i^λ) and Post-Capture Mortality (PcM_i) Scoring in an ERA Context

Within the scheme of general ERA, Encounterability (q_i^{h}), Selectivity (q_i^λ), and (PcM_i) were initially evaluated from literature review and/or expert/professional opinion, and expressed in semi-quantitative terms, namely risk designations of LOW, MEDIUM & HIGH given certain conditions. In this form, they were not eligible for utilization with the SAFE method. However, they may be transformed into tailored, expressly numerical inputs via equating the risk designations as proportional break-point values on a 0-1 scale, for example: LOW = 0.33; MEDIUM = 0.67; HIGH = 1.0. Therefore, for maximum synchrony with the mathematical architecture of the Zhou et al. LL equation, I was compelled to derive an ERA Level 2 risk score assessment regarding the component of "encounterability," which may then be transformed into the numerical, scale value of the variable of q_i^h for the purposes appropriate utilization by the model, should the value not be published directly within the contemporaneous literature. When values for any of these three variables were found to be present in the literature, the numerical finding would simply be directly migrated into this study's analysis. Fortunately, the IOTC produced an ERA Level 2 assessment on the pelagic shark bycatch of the Indian Ocean high seas longline fishery relatively recently (Murua et al., 2012), and thus a sizeable portion of the work had been completed on this front, but by no means entirely. In summary, this present study utilized primarily the Murua et al. (2012) ERA Level-2 findings to populate catch mechanism variable values for species under analysis as well as manually derived values for shark species not previously assessed when necessary to complete the numerical prerequisites for a viable analysis.

Deriving Values for Encounterability (q_i^{h})

Regarding encounterability specifically, the variable was scored using habitat information modified by bathymetric information. Higher risk corresponds to the gear being deployed at the core depth range of the species. In Zhou et al. (2011), Zhou & Fuller (2011), and Zhou, Fuller, & Daily (2012), the scale-value transformations of the encounterability risk scores are equal to the values of 0.33, 0.67, and 1.0 for species defined by ERA Level 2 as categorically either LOW, MEDIUM or HIGH risk/probability for encountering gear via relevant ERA encounterability criteria; specifically, encounterability risk was determined by the probability of vertical overlap of gear with core habitat framed by the bathymetric profile of the corresponding demersal plain. Therefore, the two operative categorical considerations for risk score designation for encounterability within the ERA Level-2 framework are: Habitat (and its subdivisions) in the context of Bathymetry (and its subdivisions).

Consideration of Habitat

Mirroring classification categories used in ERA assessment, a species' habitat is first categorized by primary residence in one of the two following ecological spaces, which are known to yield specific overlap configurations in relation to a gear, namely: "benthic" (bottom) and "pelagic" (water column) (ignoring the third "air column" category as it is not relevant to our study) (Hobday et al., 2007 [AFAM Report R04/1072]).

The two relevant habitat classes/categories are defined and subdivided accordingly:

1) Benthic habitat—this bottom habitat is further categorically cleaved in relation to the habitat's substrate hardness, classified as the following:
    a) "Hard" (e.g. rock, coral, etc.)
    b) "Soft" (e.g. silt, sand, mud)

2) Pelagic habitat—species resident within this particular, broad ecological/habitat category may further be binned by their location of residence within the water column, divided into four commonly defined vertical spaces:
    a) “Epipelagic” (upper third of water column)
    b) “Mesopelagic” (middle third of water column)
    c) “Benthopelagic” (bottom third of water column)
    d) “Bathypelagic” (deep ocean; 700–3,000 m)

These spaces within the water column are not arbitrary and exhibit distinct environmental properties and rapid gradients which approximate physically restrictive ecotones (Forbes, 1856; Hedgpeth, 1957; Briggs, 1974; Spalding et al., 2007). Ecological and life history segregation along these vertical ecotones, as in all modes of ecological phenomena marine or otherwise, drive in evolutionary terms general typologies among resident organismal morphology, distinct faunal assemblages, biomass allotments, and species behavior. Lastly, species occurring in the little-known parts of the deep ocean (700–3,000 m), where the water column is poorly defined, may be categorized as “Bathypelagic.”

Consideration of Bathymetry—"Bathymetry Check”

The aforementioned “bathymetry check” is used to check the encounterability risk score for false positives (species scored HIGH but should be lower) and is similarly scored according to the same three state categorical structure of HIGH, MEDIUM, or LOW [risk/probability]. The bathymetric range of a species is categorized based on demersal provinces. A species may be vulnerable to a particular gear type due to a common position within the water column or on a common bottom type—designating a hypothetical species as high potential risk for example; however, if the species occurs outside the bathymetric range of a fishery, the actual risk is likely lowered. The bathymetry check is broadly used to flag for potential false positives in risk attribution. The following demersal provinces are given accordingly:

1) "Inner Shelf" (≈ 0 – 110 m)
2) "Outer Shelf" (≈ 110 – 250 m)
3) "Upper Slope" (≈ 250 – 565 m)
4) "Mid-Upper Slope" (≈ 565 – 820 m)
5) "Mid-Slope" (≈ 820 – 1100 m)
6) "Lower slope / Abyssal" (≈ 1100 – 3000 m)

Revised Encounterability Scoring Key for Present Study

Table 6 represents the values for habitat and bathymetric sub-delineation as operative within the specific conditions of India's oceanic EEZ and its constituent longline fishery. The table also introduces a revised scoring system. Although broadly similar to the standard [LOW, MEDIUM, HIGH] structure, this scorecard increases functional resolution through the introduction of defined intermediate categories [LOW-MEDIUM & MEDIUM-HIGH], and requisite transformed scale-value equivalents.

The justification of specific risk scores given to habitat categories are outlined in an in-depth manner following the table. This is done due to the perceived importance in the communication of the procedural basis for parameter value designation in this context (Daley et al., 2007), as designations could be rightly construed as somewhat arbitrary or overly subjective if criteria are not presented in a satisfactory manner. Furthermore, significant attention was payed to specific conditions operative within the Indian geographic context which provide further nuance and credibility to the nature of value allotment decisions herein described.

Table 6. Revised ERA risk-scorecard for longline bycatch species extant within India's oceanic EEZ.

Habitat Dependent Encounterability			Bathymetry Check			Risk Category Scorecard & Scale Value Equivalence		
Habitat			Province					
Name	Def.	Score	Name	Depth range	Score	Risk Cat.	Score	Scale Value
Hard Bottom	Rocks, reefs etc.	Low	Inner Shelf	≈ 0–110m	Medium	High [H]	3	0.999
Soft Bottom	Sands, muds, silt etc.	Low	Outer Shelf	≈ 110–250	High	Medium-High [MH]	2.5	0.8325
Epi-pelagic	Top third of the water column, near surface	High	Upper Slope	≈ 250–565	Medium	Medium [M]	2	0.666
Meso-pelagic	Middle third of the water column	Medium	Mid-Upper Slope	≈ 565–820	Low	Low-Medium [LM]	1.5	0.4995
Bentho-Pelagic	Bottom third of the water column, the bottom	Low	Mid-Slope	≈ 820–1100	Low	Low [L]	1	0.333
Bathy-pelagic	Deepwater, ≈700–3000	Low	Lower slope/ Abyssal	≈1100–3000	Low			

Consideration of Operative Gear Depth of the Longline Fleet to Anchor High Risk Depth Regime

Regarding longline gear, the depth of operation is fundamental to defining intersection with target species as well as to the larger domain of organisms that might be eligible to be affected by such an introduced response point (gear); ergo, the understanding of the operational depth of gear is critical to defining the impact of tuna longline on target and bycatch species alike (Bigelow, Musyl, Poisson, & Kleiber, 2006).

Target species residence depth. In the Indian Ocean, *Thunnus albacares* are found in warmer waters and are mainly caught at depths of 40–230 m (Suzuki & Kume, 1982; Yang & Gong, 1987; Boggs, 1992). However, yellowfin tuna display a marked modal depth distribution (at least in the Gulf of Mexico), tending to spend a greater percent of nighttime hours in the uniform surface layer (32%) as opposed to daylight hours, more of which were spent at depth (12%; in the uniform surface layer), albeit the proportion of time spent above 100m varied only between (90.0%) to (99.8%) between daylight and nighttime, pointing to a strong linkage of possible encounterability around the 100m depth band (Hoolihan et al., 2014). Aside from a somewhat strong aversion to the 8.0°C point in the vertical temperature gradient, these fishes have been known to dive to depths of 984m in the gulf of Mexico (Hoolihan et al., 2014) and even deeper to at least 1600m in the Pacific (Schaefer, Fuller, & Aldana, 2014); it is likely fair to claim that the depth band with a mean at around 100m extending upward nearly to the surface defines a core preference and optimal space for encounterability.

Plausible gear depth of small / medium domestic LL fleet. The average, rough maximum of the catenary depth estimate for fishing gear has been set by around 170 to 190 m for shallow gear with five branch lines and hooks deployed between successive floats (HBF) in the Japanese longline fishery, with the deepest empirical records of hook depth on shallow-set gear found to range from 100 to 160 m (Hanamoto, 1974) and 122 to 178 m (Nishi, 1990). The existence of a bourgeoning small domestic LL fleet in India (GOI, 2011) has been catalyzed in recent years due to the activity of a targeted government management action, which was has subsidized the refurbishing of coastal trawlers to small, oceanic longlines (18-22 m). Thus, it is fairly safe to assume that at least a shallow gear depth band (0-150 m) is covered by a component of total longline gear effort within this fishery.

Plausible gear depth of foreign industrial LL fleet. Although the gear activity specifications and/or performance dimensions of the international industrial fleet operating within boundaries of India's EEZ under the LOP program are not defined (or known) in great detail, a general estimate thereof may be derived through broadly assumed symmetries with the gear action and specifications in surrogate, equivalent vessels with identical targets in proximate waters. Theoretically, the only difference between the Chinese high-seas longliners operating in the Northern Indian ocean (and Arabian Sea) and those active within the literal jurisdictional boundaries of India's EEZ is minute geographical arrangement—that is, the vessels in question diverge from exact relevancy only by virtue of their operation within the jurisdictionally exterior high-seas just beyond the territorial limits of the Indian EEZ. By virtue of targeting the same species within a highly proximate geographical relationship, they may be viewed as largely paradigmatic of tropes evinced generally by similar ventures with respect to vessel size and target design, and therefore their characteristics may be assumed as being generally homologous with the gear character utilized “just across the way” by industrial class longliners operating within EEZ waters.

Using depth monitors to derive empirical estimates of longline catenary structure, for a pair of Chinese high-seas longlines (registered as: “Hua Yuan Yu 18” [IOTC00823] & “Hua Yuan Yu 19” [IOTC00835]), Xu et al. (2006) determined that (59%) percent of the hooks fall into 200-400 m depth for these vessels. It is broadly assumed that a longline depth range of similar magnitude and location within the water column is being utilized by the industrial LOP vessels active within the explicit territorial boundaries of the Indian Oceanic EEZ.

Plausible combined gear depth range for total oceanic LL sector. Between the two fleets (viz., small/medium domestic long-liners and foreign industrial long-liners operating in India’s EEZ under the LOP promissory scheme), a maximum possible operational depth range of 25m (min. depth; from plausible min. depth of small/medium domestic LL fleet) to 400m (max depth; from maximum plausible depth of foreign industrial LL fleet) is within the realm of possibility; however, a more central subdivision of that range likely defines the true mean status of gear action (in terms of depth value) for the oceanic yellowfin tuna longline fishery across the entire range of active fleets within the fishery, or specifically with respect to the mean character of all LL fleets contributing effort to the fishery.

Anchoring high-risk habitat. In light of all considerations previously outlined, the Oceanic LL tuna fishery of the Indian EEZ is probably well defined by a depth range of 50-250m for core gear depth, and thereby defining the conditions of a HIGH-risk designation and affiliate scale value equivalent (0.999) for bycatch within this depth range. This core effort depth is broadly equivalent to the classical demarcation of the epipelagic zone, and, thus, unless otherwise given in greater detail through the species-specific published value, epipelagic oceanic sharks should expect to receive a HIGH-risk designation for this parameter in turn when derived natively in the course of this study.

Rationale for mesopelagic risk score. Retreating from the High Risk epipelagic towards depth in the next relevant bathymetric tranche, the mid-column (mesopelagic zone) will—by the basic nature of recessed distance to core gear depth range—be privy to dampened encounterability effects even within the context of an identical areal distribution area. The mesopelagic zone is larger vertically speaking than the epipelagic zone, thus reducing likelihood of encounter with gear, assuming that mesopelagic bycatch species of interest are occupying consistently the full breadth of the mesopelagic zone largely equally, which may not necessarily be accurate. However, even though the bottom extrema of the mesopelagic may be well below the depth of any utilized longline operations targeting large tunas identified in the geographic sector, the direct abutment with high risk epipelagic zone still places many species in a condition of frequent habitat incursion, as the epi/mesopelagic transition zone (commonly cited as around 200m in depth beyond the shelf [Forbes, 1856; Hedgpeth, 1957; Briggs, 1974; Spalding et al., 2007]) is right at the boundary of likely mean catenary depth of small/medium longline operations (rough approx. 125-150m [Hanamoto, 1974; Nishi, 1990]) and shallower than mean catenary depth of known industrial LL ventures in the Arabian Sea (rough approx. 250-350m [Xu et al., 2006]).

Additionally, many oceanic species across the food web are known to variably straddle this transition zone existing to so some degree in both the epipelagic and mesopelagic, though in different temporal proportions depending on primary regime of residence and other factors (Lampert, 1989; Weng & Block, 2004; Shepard et al., 2006; Hoolihan & Luo, 2007; Hoolihan et al., 2014; Schaefer et al., 2014). One typology of this tendency of species to straddle depth zones is found in the various examples of diel migration exhibited by a cross sections of the elasmobranch clade pertinent to this study (Weng & Block, 2004; Shepard et al., 2006). Also, mesopelagic shark species such as the Crocodile Shark (*Pseudocarcharias kamoharai*) and to some extent gulper shark (*Centrophorus granulosus*; though deeper general range) are frequently caught as bycatch within longline fleets (Akhilesh et al., 2011) in this area of the world and across their range to some degree. Therefore, it is known that such mesopelagic species are transient to the extent that they encounter fishing effort even when said effort is targeted vertically a respectable amount above their core habitat depth, at least theoretically.

By this chain of logic, regarding the deployment tropes of the relatively modest/moderately sized foreign industrial vessels operating in close proximity to the southwestern and fully oceanic district of the outer Indian EEZ, the author feels that assigning the mesopelagic habitat as MEDIUM risk and thus a transformed scale value of (0.666), rather than the LOW risk demarcation it would have otherwise received via a straight forward bathymetry check, is valid.

Rationale for coastal / inshore epipelagic risk score. Being that the small/medium domestic LL fleet does not have the capacity for the multi-week/month expeditions that the larger and more specialized industrial vessels exhibit, they often do not have the long-form mobility range of the larger vessels, making these vessels prone to fish with a less directed oceanic concentration, likely at the cusp of the transition zone into the oceanic sector (~50–70 km offshore) and shelf break (Ramachandran, 2014; Sinha, Anrose, Pratyush, & Babu, 2017). That being the case, it is fair to think of the delimitations between overt sectors by these vessels to be more porous, extending a significant amount of effort around the transition zones, and thus fishing in a manner that may be straddling both sectors with some frequency. In so doing, such vessels and their particular activity profiles may be generating bycatch mortality impact at the undefined interstitial area between coastal and oceanic zones. Such that the aforementioned scenario may define a predominant real condition, coastal and inshore epipelagic habitat risk scores could be justifiably upgraded to MEDIUM risk, rather than the zone dependent LOW risk. If nothing else, this should be considered as a precautionary override which is within the management designating capacity of the ERA process.

Deriving Values for Selectivity (q_i^λ)

Selectivity or (q_i^λ) is the second of the three catch mechanism parameters. In theory, a number of different complex behavioral and population considerations go into estimating a quantity for selectivity (q_i^λ). Among different studies utilizing the ERA mode, the manner in which selectivity has been derived has varied (Cortés et al., 2010; cf. Murua et al., 2012); however, as prescribed via Zhou et al. (2011), Zhou & Fuller,

(2011) and Zhou, Fuller, & Daily (2012), a valid scheme for selectivity risk scoring (and thus scale value allocation) may be based solely on the on the adult sizes of the organisms in question, and specifically the size of the organism in relation to the size of the specific gear.

Size-dependent selectivity is based on average length at maturity for bycatch species (Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012). Organisms at the plausible extremes of the faunal size within the fishery; specifically, those <10 cm or >500 cm, are defined as LOW risk for selection (Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012). The transformed scale value for LOW risk is given s 0.33 (Walker, 2005; Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012).

Organisms that are just slightly bigger on the lower end of the size scale or smaller on the higher end of the scale as subject to increased risk of selection; thus, organisms between 10–20 cm & 400–500 cm are defined as MEDIUM risk (Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012), and they attain a corresponding transformed scale value of 0.67 (Walker, 2005; Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012). The 400–500 cm size cohort entails some of the largest adult sizes of the next tranche of large oceanic sharks and may plausibly group some of the largest adult members of classic oceanic residents such as many requiem sharks (blue shark, silky shark, dusky, oceanic whitetip, and others [Compagno, 1984; Compagno, 2001]).

Finally, the HIGH risk category is defined by organisms between 20 and 400 cm (Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012), which is given a high-risk score or a value of 0.999 (Walker, 2005; Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012). Organisms of this size range within the oceanic longline fishery are considered to be completely "selected-for" by virtue of the optimal physics of the gear and similarity in size to the target species of yellowfin tuna or oceanic tunnies generally. The size cohort from 20–400 cm truly contains essentially all possible sharks across their entire life history (Compagno, 1984; Compagno, 2001), so, unless caveated by specific experimental evidence (i.e. via primarily Murua et al., 2012; but also Cortés et al., 2010; Gallagher et al., 2012; Cortés et al., 2015, etc.), it will be safe to simply assume this parameter to be HIGH risk (i.e. 0.999) for most species of shark (Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012), unless specific values for this parameter were derived previously in the literature as just mentioned. The full range of uncertainty may, however, be expressed by virtue of the forthcoming Bayesian hierarchical design which may estimate the range of uncertainty [from 0.333–0.999] across the total possible scale parameter space.

Deriving Values for Post-Capture Mortality (PcM_i)

The final variable in the triad of catch mechanism parameters is Post-Capture Mortality (or PcM_i). For species that are caught by the gear and then discarded alive, post-capture mortality measures the mortality probability of the species after being returned to the water. The values for this parameter were drawn from the literature and/or expert input where available (Murua et al., 2012), but this metric is generally a hard feature to measure empirically. In this regard, this study took a fairly precautionary approach, either using values specifically published at a per-species level (and not at a genera level or otherwise), or when deriving risk score estimates for unpublished species as required, the author chose to universally apply a designation of MEDIUM to HIGH risk as a risk range for post-capture mortality (not to be confused with the risk designation MEDIUM-HIGH, which results in a single transformed scale value and is not a range). The M-to-H range corresponding to the scale values of (0.666-0.999). These upper and lower values inform [a, b] inputs on a uniform prior of the Beta distribution representation of PcMi within the forthcoming Bayesian hierarchical model. Although the M-to-H range designation was the specific rule observed ubiquitously for unpublished species, it was based on the logic of a more general guideline for designating PcMi values thusly outlined: for species evincing LOW, MEDIUM, and HIGH risk of post-capture mortality, corresponding transformed scale values were PcMi = 0.333, 0.666, 0.999, respectively (Walker, 2005; Daley et al., 2007; Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012).

Pre-Analysis Operations, Part II: Deriving Fishing Mortality Values (F) for LL Fishery Dominant Target Species *Thunnus albacares* in India's Oceanic EEZ

A key data prerequisite for the ultimate derivation of (shark) bycatch mortality (F^{Shk}) via the Zhou et al. LL equation is first calculating fishing mortality for the primary target species (or multiple target species) of the fishery, which is incorporated mathematically as a component within the aforementioned ρ variable. The target species' fishing morality term is highlighted in red and encircled for emphasis in a copy of the ρ sub-equation, provided again for convenience below (Equation 3):

$$\rho^{\mathrm{T}} = \frac{1}{n}\sum_{\mathrm{i}=1}^{n} \frac{\enclose{circle}{F_{\mathrm{i}}^{\mathrm{T}}} A_{\mathrm{i,J}}}{q_{\mathrm{i}}^{\mathrm{h}}\, q_{\mathrm{i}}^{\lambda}\, A_{\mathrm{i,f}}^{\mathrm{T}}} \tag{3}$$

where (*i*) is the i^{th} target species.

In the oceanic longline fisheries of the Indian EEZ, the highest focus species is Yellowfin Tuna (Abdussamad et al., 2012a, 2012b; Hornby et al., 2015a, 2015b). In recalling the equation to garner ρ (Eq. 3), one will notice a value n, which corresponds to the number of distinct target species whose values are averaged to obtain the final value of ρ. Given the prominence of yellowfin tunas (YFT) in the oceanic longline (LL) catch—94.6% of all tunnies caught in India's oceanic fishery by one estimate (Abdussamad, 2012a, 2012b)—using exclusively yellowfin tuna as the sole target species to be factored into the ρ sub-equation seemed viable. Ergo, in this case, ρ is defined in whole by the values lent to the equation by the target species of Yellowfin Tuna. And because ρ is only concerned with one species, the search for ρ is now mostly just the search for $\mathrm{F}^{\mathrm{YFT}}$. Such as it were, the relevant ρ sub-equation could be reduced significantly, considering only one target species was being negotiated and the values of (q_i^h, q_i^λ) were assumed to be 1.0 for our primary target species based on the detailed criteria outlined in the previous section. The reduced operative ρ sub-equation in the context of this study's analysis is given below (Equation 4):

$$\rho^{\mathrm{T}} = F_{\mathrm{i}}^{\mathrm{T}} \frac{A_{i,J}}{A_{i,f}^{T}} \tag{4}$$

where i is Yellowfin Tuna (in this study).

In most data-standard cases, F (or $\mathrm{F_i}$; i simply representing the $\mathrm{i^{th}}$ specified species), time-series values for target species may have been previously published and thus eligible for directed commutation into the Zhou et al. LL equation; however, certain data/analytical paucities were operative within the purview of this study (Sinha et al., 2017), catalyzing the need for novel solutions designed in the context of "at-hand" data typologies and assets.

Specifically, no F^{YFT} time-series of sufficient utility were discovered in relation to this study's sub-region (India's oceanic EEZ explicitly) in the preliminary literature review of this topic, therefore obtaining estimates of these values in the second degree via some proxy or functional relationship became necessary to ultimately realize a value of ρ.

Although values for F^{YFT} for the oceanic region of India's EEZ where not readily available (i.e. $F^{YFT^{EEZ}}$), values for F^{YFT} for the IOTC competence area were available (i.e. $F^{YFT^{IOTC}}$) (Figure 10; Table 7). The IOTC releases summary stock assessments for all migratory and high seas species within the purview of their management area, known as the IOTC Competence Area, spanning a large swath of the Indian Ocean. (For maps of these of IOTC Competence Area and its subdivisions, see primarily Figures 12 & 13).

The most recent stock assessment for Yellowfin Tuna, the IOTC YFT 2015 Stock Assessment (see Langley, 2015 [IOTC–2015–WPTT17–30]; Langley, 2016 (IOTC-2016-WPTT18-27): "Update for 2016"), is buttressed by a variety of informative fisheries analyses and furnished by a multinational, long-time horizon data set of yellowfin tuna fishing within the Indian Ocean, making it likely the most reliable estimate available for fishing mortality ($F^{YFT^{IOTC}}$). Although it may be updated in light of new understanding, the value for fishing mortality at Maximum Sustainable Yield (F_{MSY}), once calculated, is constant across years. The value for F_{MSY} for the YFT Indian Ocean Stock is calculated by the IOTC as 0.151, C.I. 80% [0.148-0.154]. Ergo, since the value of F_{MSY}, as well as the ratio of annualized instantaneous rate of fishing mortality over fishing mortality at Maximum Sustainable Yield (F_{year} / F_{MSY}), have both been published as summary statistics (Langley, 2016), then F_{year} for the entire IOTC competence area can be trivially derived $\left(\text{i.e. } F_i^{YFT^{IOTC}_{Allgear}}; \text{Table 7}\right)$.

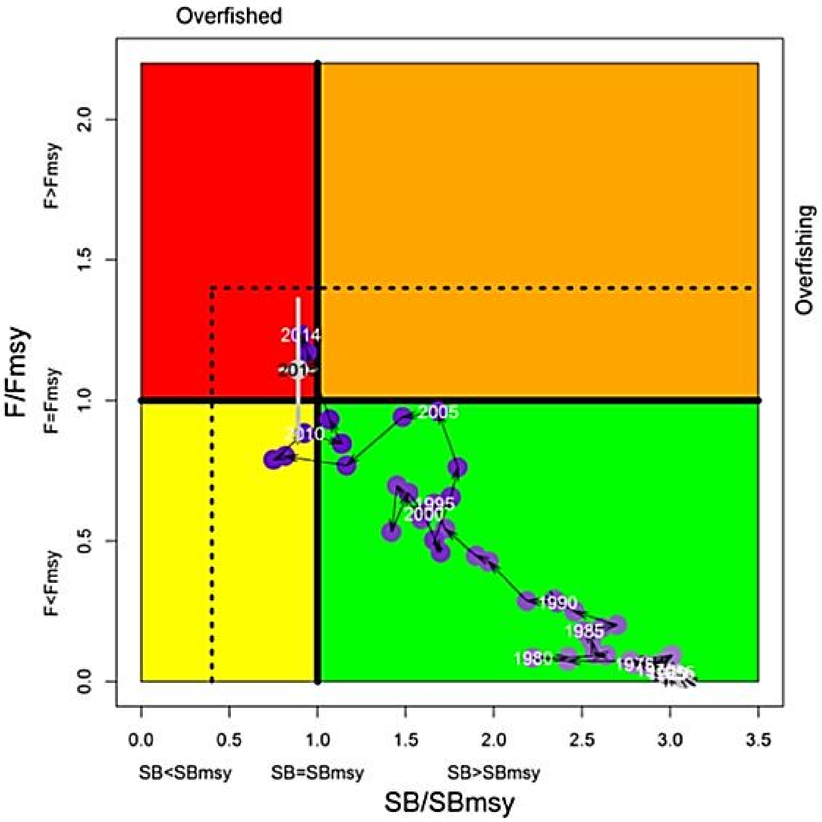


Figure 10. Yellowfin tuna: IOTC Stock synthesis Kobe plot. Blue dots indicate the trajectory of the point estimates for the B/B_{MSY} ratio and F_{MSY} proxy ratio for each year 1950–2015. The grey line represents the 80% confidence interval associated with the 2015 stock status. Dotted black lines are the interim limit reference points adopted by the Commission via Resolution 15/10 (*On target and limit reference points and a decision framework* [iotc_cmm_15-10_en.pdf]).

Table 7. Yellowfin tuna fishing mortality from IOTC Stock Assessment Synthesis Report (Langley, 2015, 2016).

Study Notation	IOTC Notation	2010	2011	2012	2013	2014
$\boldsymbol{F}_{\mathrm{MSY}}^{\mathrm{YFT}_{\mathrm{Allgear}}^{\mathrm{IOTC}}}$	$\boldsymbol{F}_{\mathrm{MSY}}$	0.151	0.151	0.151	0.151	0.151
$\frac{\boldsymbol{F}_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{Allgear}}^{\mathrm{IOTC}}}}{\boldsymbol{F}_{\mathrm{MSY}}^{\mathrm{YFT}_{\mathrm{Allgear}}^{\mathrm{IOTC}}}}$	$\boldsymbol{F}_{\mathrm{year}} / \boldsymbol{F}_{\mathrm{MSY}}$	0.85	0.80	0.91	1.05	1.23
$\boldsymbol{F}_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{Allgear}}^{\mathrm{IOTC}}}$	$\boldsymbol{F}_{\mathrm{year}}$	0.128	0.121	0.137	0.159	0.186

Although we must rely on a few a priori system assumptions (which likely exhibit some degree of unknown divergence in the real-world), it may be possible to roughly back-calculate fishing mortality for the oceanic region of the Indian EEZ (i.e. $F^{\mathrm{YFT}^{\mathrm{EEZ}}}$) by only utilizing the following values (defined annually for the years 2010-2014):

1) Total yellowfin tuna fishing mortality for IOTC Competence Area $\left(F^{\mathrm{YFT}_{\mathrm{Allgear}}^{\mathrm{IOTC}}}\right)$,
2) Yellowfin tuna longline catch (tonnes) for the Indian Oceanic EEZ $\left(C^{\mathrm{YFT}_{\mathrm{LL}}^{\mathrm{EEZ}}}\right)$,
3) Yellowfin tuna all-gear catch for IOTC Competence Area $\left(C^{\mathrm{YFT}_{\mathrm{Allgear}}^{\mathrm{IOTC}}}\right)$,
4) Catch ratio between YFT by LL in India's Oceanic EEZ to total YFT in IOTC Competence Area $\left(\frac{C^{\mathrm{YFT}_{\mathrm{LL}}^{\mathrm{EEZ}}}}{C^{\mathrm{YFT}_{\mathrm{Allgear}}^{\mathrm{IOTC}}}}\right)$,
5) Area ratio between IOTC Competence Area and area Oceanic EEZ $\left(\frac{A_{\mathrm{IOTC}}}{A_{\mathrm{EEZ}}}\right)$.

Parent & Child Area Notation

India’s Oceanic EEZ is effectively a smaller geographical subunit (child area) of a larger geographical unit (parent area), which in this case is defined to be the total IOTC Competence Area (Figure 11).

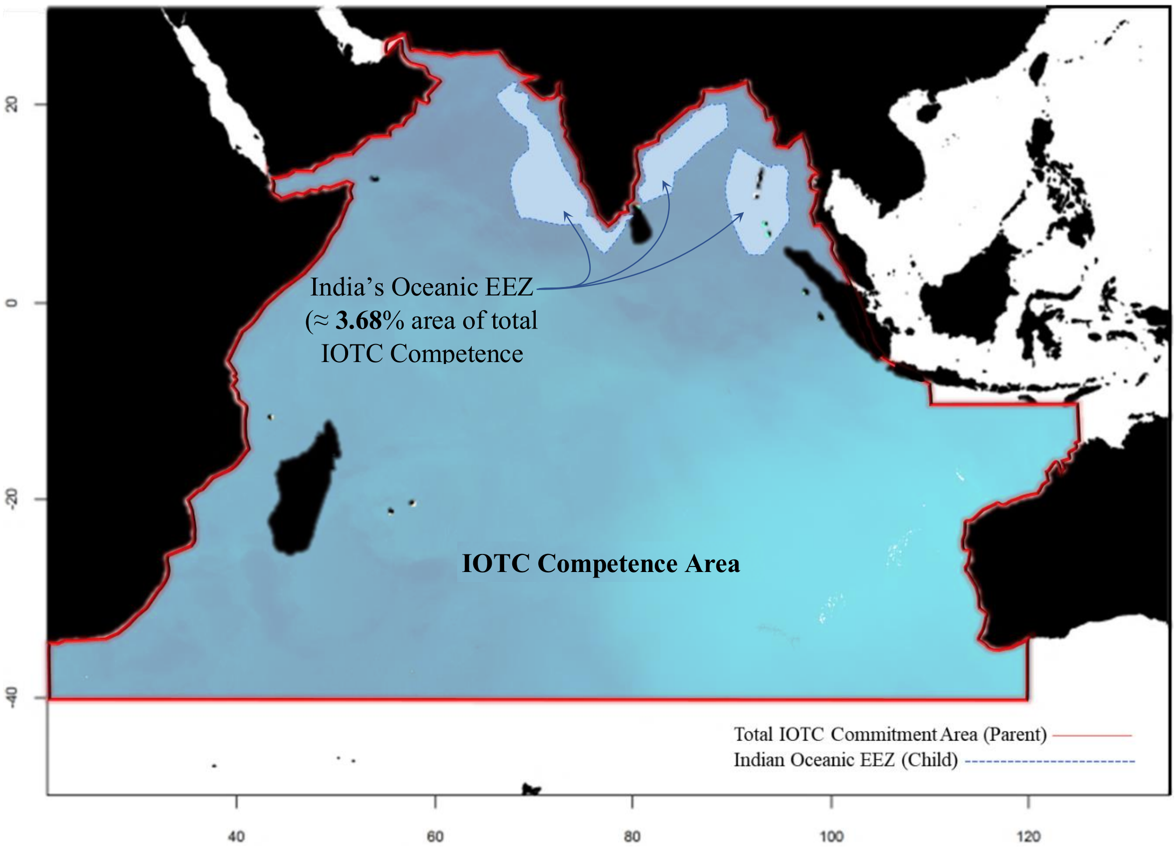


Figure 11. Scale representation of child area (India’s oceanic EEZ) nested *within parent total area* (IOTC competence area). Visually represents core conceptual trope for areal proportion between child and parent area as basis for scalability of fisheries values of interest. Competence Area and Commitment Area are synonyms.

The child area (India’s Oceanic EEZ) is completely couched within the boundary of the parent area (IOTC Area of Competence); therefore, the catch and biomass values respectively of the child area are directly proportional to the catch and biomass values of the parent area. Each value (or both) may be simply calculated as the product of the ratio of the child area (Oceanic EEZ: 1,889,709 km^2) to the total parent area (total IOTC Competence Area [which includes Oceanic EEZ area]: 51,260,364 km^2) or (1,889,709 / 51,260,364) multiplied times either the original Catch (or Biomass) of the IOTC Competence Area. The child area or the Indian Oceanic EEZ occupies roughly 3.68% of total area, i.e. 3.68% of the total extent of the IOTC Competence Area (Figure 11).

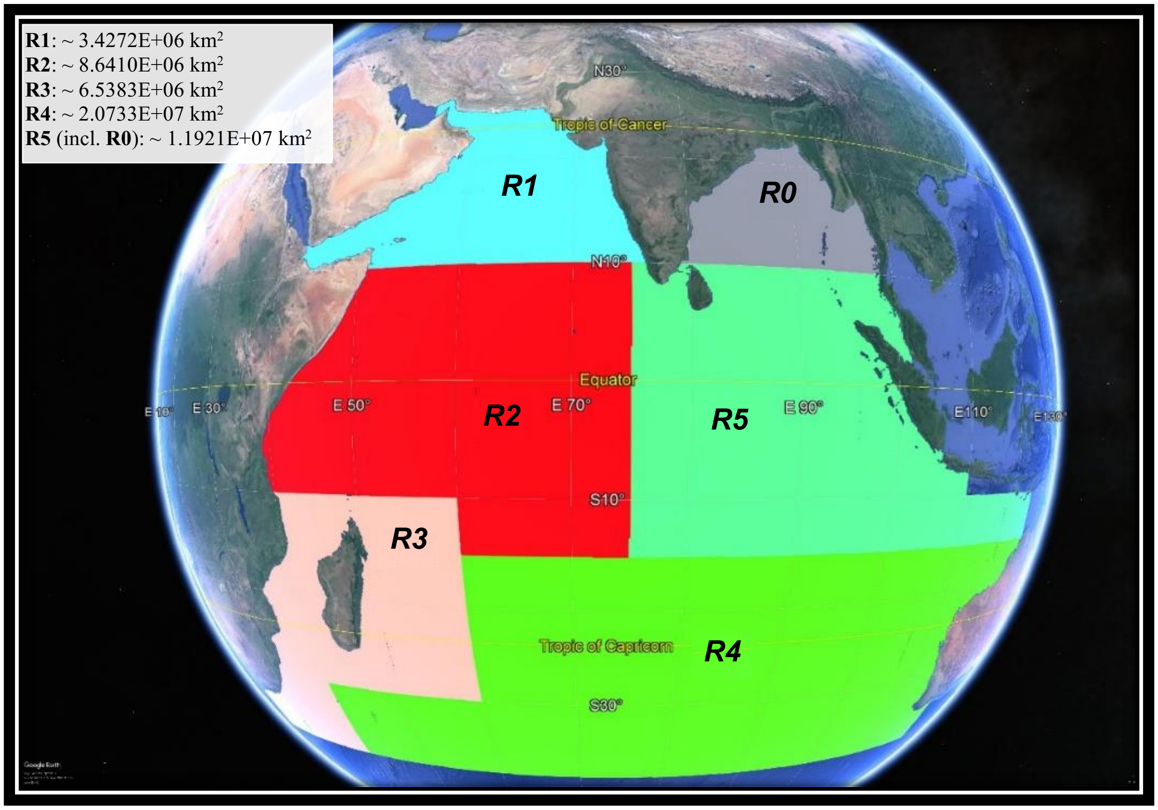


Figure 12. IOTC competence area & IOTC managment sub-region boundaries (R0–R5).

Assuming catch and effort per unit area is homogenous given no other information about catch in India's oceanic EEZ (initially), and the fact that F_{child} (i.e. Fishing Mortality for the child area) is equal F_{parent} for any arbitrary child subdivision, in so far that the (Catch / Area) ratio for the child remains in a constant proportion to the (Catch / Area) of the parent, it becomes feasible to derive values of F^{YFT} for our sub-region of interest (Indian Oceanic EEZ) via proportional downscaling of the known annual F^{YFT} values (Figure 10; Table 7) of the Indian Ocean Tuna Commission competence area (Figures 11, 12 & 13) to the waters of the Indian Oceanic EEZ (Fig. 11).

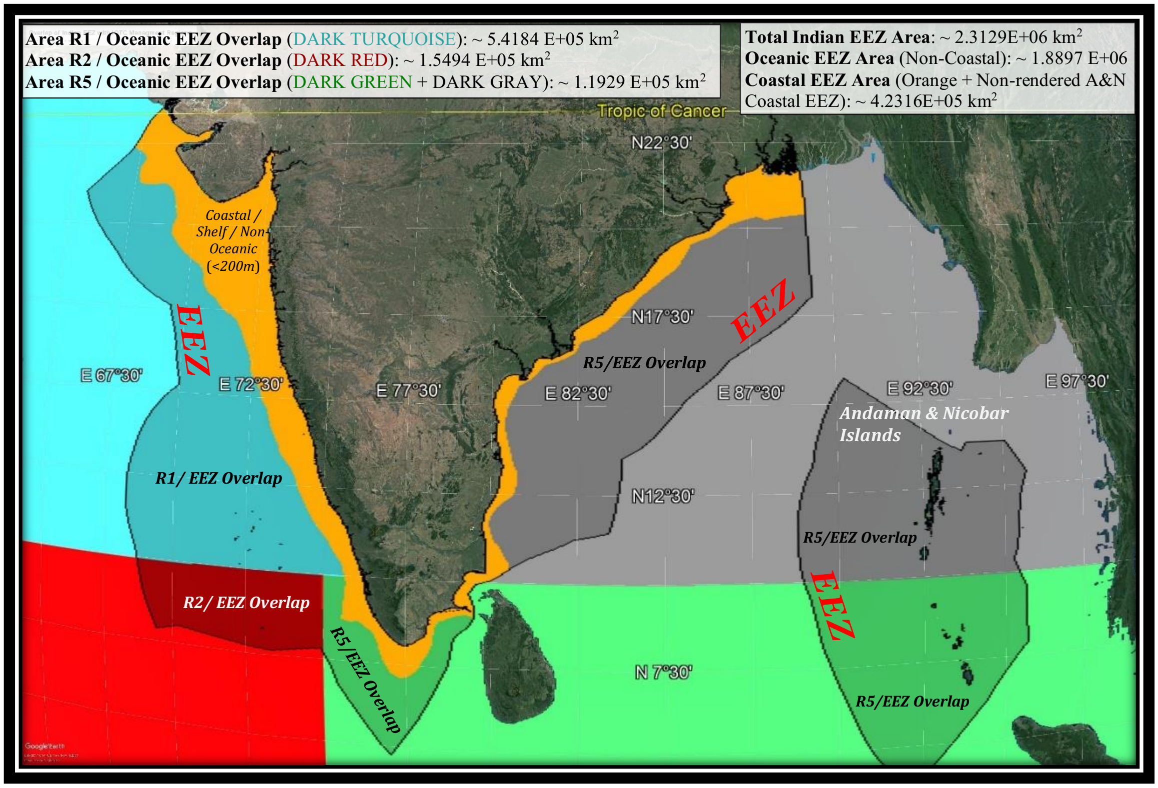


Figure 13. Relevant management bounding polygons and area values for Indian EEZ & subcomponents.

Proof for Derivation of Instantaneous Fishing Mortality Scaled from Parent to Child sub-Regions when Biomass is Proportional to Area (Proof 1)

The objective is the determination of Fishing Mortality Rate (F_{EEZ}) for yellowfin tuna (*Thunnus albacares*) in India's oceanic EEZ considering there are no explicitly available published values for the species in this sub-region. Although outright fishing mortality rates have not been produced within the known literature, available datasets do include: published values for yellowfin tuna fishing mortality for the IOTC competence area stock (F_{IOTC}); Oceanic Longline Catch ($C_{EEZ, LL}$) estimates for India's Oceanic EEZ Area (from various studies); published total catch estimates (C_{IOTC}) for total IOTC competence area; and Area values for Indian Oceanic EEZ (A_{EEZ}) and IOTC competence area themselves (A_{IOTC}). However, from these datasets alone, the author intends to prove how in fact fishing mortality rates for the Indian Oceanic EEZ may be derived. The proof is given through the list of equations and interjecting descriptions given below:

The basis of deriving the initially unknown instantaneous fishing mortality rates for yellowfin tuna in the Indian Oceanic EEZ (child area) based upon the *known* values of the instantaneous fishing mortality rates values in the IOTC competence area (parent area) is based structurally on the on the working assumption that biomass (i.e. the YFT stock) is distributed largely homogenously throughout the competence area. That working assumption is substantiated in the IOTC YFT Stock Synthesis report, which states: "Catch data indicates that yellowfin is distributed continuously throughout the entire tropical Indian Ocean…" (Langley, 2015). Therefore, let Biomass = B || Area = A. (To Note—variables introduced will remain the same throughout the proof).

On the basis of the prior assumption of evenly distributed stock throughout the IOTC competence area, stock Biomass could be reasonably assumed to be proportional to Area, updated continuously (Equation 5):

$$B \propto \mathrm{A} \tag{5}$$

Next, consider the equation for Catchability given by Gulland (1969) as Equation 6, where q = Catchability || C = Catch (Yield) || E = Fishing Effort:

$$q = \frac{BC}{E} \tag{6}$$

Equation 7 below identifies Instantaneous Fishing Mortality (F) as the product Catchability (q) and Fishing Effort (E). Via the common variables of Catchability (q) and Fishing Effort (E), the defined equation for fishing mortality (F) (Equation 7) is then linked to Gulland's equation for Catchability above (Equation 6). By combining these equations through substitution of equivalent terms, a direct, mathematical relationship among the variables of Instantaneous Fishing Mortality, Catch, and Biomass is proven, and given via the expressions in Equation 8. Let F = Instantaneous Fishing Mortality:

$$F = qE \tag{7}$$

$$\therefore\ F = C/B \quad \Longleftrightarrow \quad B = C/F \tag{8}$$

Biomass is directly proportional to area (shown previously); ergo, 40% of IOTC commitment area has 40% YFT stock biomass, 50% area has 50% biomass, 60% area has 60% biomass, and so on. By setting initial IOTC commitment area YFT biomass equal to a scale value of 100% (even though its exact unit value *is not* known), one may conclude that any ratio of B_{child} (x %) : B_{parent} (100%) is equal to the value of the ratio of A_{child} : A_{parent} (whose exact unit value *is* known) (Equation 9). Since the ratios of B_{child} :

B_{parent} and $A_{\text{child}} : A_{\text{parent}}$ have been established as equal, we may now substitute in shared variables in the $B_{\text{child}} : B_{\text{parent}}$ ratio to ultimately solve for F_{child} (or F_{EEZ} [India's EEZ]). For the variables of child biomass (B_{child}) and parent biomass (B_{parent}), recounting from a previous equation that any Biomass (B) may be given as Catch (C) / Fishing mortality (F) (Equation 8), B_{child} may be rewritten as $C_{\text{child}} / F_{\text{child}}$, and, likewise, the variable of B_{parent} may be rewritten as $C_{\text{parent}} / F_{\text{parent}}$ (Equation 10), leaving the $A_{\text{child}} : A_{\text{parent}}$ ratio equal to the transformation of the $B_{\text{child}} : B_{\text{parent}}$ ratio, such that the value B_{child} is given as C_{child} / F_{child} and the value of B_{parent} is given as $C_{\text{parent}} / F_{\text{parent}}$ Manipulating the prior equation (Equation 10) so that it is rendered to expressly solve for the variable F_{child} gives us Equation 11.

$$\frac{B_{\text{child}}}{B_{\text{parent}}} = \frac{A_{\text{child}}}{A_{\text{parent}}} = \frac{x}{100} \tag{9}$$

$$\frac{A_{\text{child}}}{A_{\text{parent}}} = \frac{\dfrac{C_{\text{child}}}{F_{\text{child}}}}{\dfrac{C_{\text{parent}}}{F_{\text{parent}}}} \tag{10}$$

$$\frac{C_{\text{child}}}{C_{\text{parent}}} \bullet F_{\text{parent}} \bullet \frac{A_{\text{parent}}}{A_{\text{child}}} = F_{\text{child}} \tag{11}$$

With the final conceptual construction accounted for in Equation 11, the only task remaining is the substitution of the conceptual placeholders with the real-world values that correspond to the tenets of the variables presented. In order to complete the task of deriving instantaneous fishing mortality for YFT with respect to India's Oceanic EEZ

(F_{EEZ}), the following values/data-streams were furnished from preexisting sources and research: C_{IOTC} (i.e., C_{parent}) and F_{IOTC} (i.e., F_{parent}) for yellowfin tuna were generated via IOTC Stock Synthesis reports (Langley, 2015, 2016); area values for A_{IOTC} (i.e., A_{parent}) and A_{EEZ} (i.e., A_{child}) came from GIS polygon calculations (Claus et al., 2018; Nagle, present study); and lastly, longline catches of yellowfin tuna from the Indian oceanic EEZ (C_{EEZ}) (i.e., C_{child}) were generated from a collection of sources, where j is the j^{th} source and j={1,2,3} [j=1 is Abdussamad et al. (2012a, 2012b); j = 2 is Hornby et al., (2015a, 2015b); j = 3 is India's National Reports to the Scientific Committee of the IOTC by the Fisheries Survey of India (Various Authors, 2010-2015)]. Together, these known values / data-streams accommodated the derivation of annualized values of F_{EEZ} via straight forward algebraic means, which was both the express goal of this poof as explicit values for F_{EEZ} where not available outright, yet such values were structurally crucial to the execution of the broader SAFE LL analyses. The final equation concerning the derivation of F_{EEZ} is given below (Equation 12). It is structurally identical to Equation 11; however, the generalized child/parent notation is exchanged for more specific references to the real values utilized in the research.

$$\therefore \quad \frac{C_{\text{EEZ}}}{C_{\text{IOTC}}} \bullet F_{\text{IOTC}} \bullet \frac{A_{\text{IOTC}}}{A_{\text{EEZ}}} = F_{\text{EEZ}} \qquad \blacksquare \tag{12}$$

To note—this value (Equation 12) is not technically calculated outright, at least in the deterministic manner shown, as these variables (viz., C_{IOTC}, F_{IOTC}, C_{EEZ}) are defined as stochastic parameters within the forthcoming Bayesian Hierarchical Model in order to introduce relevant uncertainty at each known equation variable (see Chapter III); values from sources are input as observations/data with the parameters subjected to an identical algebraic equation within the Bayesian model however, so the basis for validity remains.

Pre-Analysis Operations, Part III: Spatial Analysis—Deriving FJA, $A_{i,J}$, $A_{i,f}$ for Target & Bycatch Species

The primary purpose of the spatial analysis module is to furnish values for the overarching FJA, $A_{i,J}$ (core range/habitat distribution within the FJA), and $A_{i,f}$ (LL effort distribution within core range) for the target species *Thunnus albacares* (Yellowfin Tuna) as well as the 31 species of shark analyzed. Additionally, $A_{i,f}$ is defined annually, so values for $A_{i,f}$ are calculated for every year within the time period utilized i.e. [2010-2014] for every species.

Populating Spatial Layers with Relevant Data

Many of the core data points requisite for populating the model, specifically those with an areal dimension, are summated totals of values arising across a spatial or geographic layer comprised of cells (i.e. grids), and often a mathematical relationship between equivalent cells on parallel layers. These cells define the value of a feature as it can be thought to exist across a quantified and discrete spatial delineation. Populating the values within cells for a number of spatial layers is necessary for the production of values such as $A_{i,J}$ and $A_{i,f}$ for targets and bycatch similarly. The conceptual features communicated by each layer, the possible numerical values of constituent cells, and criteria used to populate them as such, as well and the mathematical relationship between cells as they interact across layers, are outlined subsequently.

Species Native Range Distribution Layer (L_1)

The spatially defined native range (viz., habitat distribution or other similar monikers; core range usually meaning specific range within the defined FJA) of relevant species is a crucial consideration, specifically within the design of this study's fisheries equations. This was populated into the respective spatial layer, defined as the species habitat distribution layer, through the construct of Species Occurrence probability as exhibited across cells representing discrete geographical areas. Values for Species Occurrence probability fall within 0 to 1, where one equals maximum species preference for associated habitat typology, and thus results in the near certainty of its residence within that geographical allotment (i.e. cell); alternatively, a value of near 0 represents the homeostatic and biogeographical extent of plausible range. Specific grid wise (cell-wise) values for these data comes from the AquaMaps project (Kaschner et al., 2016 [Version 08/2016, www.aquamaps.org]). The primary outputs of the AquaMaps project are individualized species distribution maps, mapped according to the primary statistic of Species Occurrence Probability or (P_c); the result of this is the production of species distribution "heatmaps" as opposed to simply uniform range representation via a geographic polygon with boundaries defined by the most extreme extent of field sightings. The values are output on a [0.5° Lat × 0.5° Long] demarcated geographic heatmap. The per-cell output is the probability product of a number of broadly determinant environmental predictor variables operative in the bounding of species habitat preference; this is cumulatively referred to as the environmental envelope. The environmental envelope that produces the per cell output (Occurrence Probability) is defined by the following probabilities (Equation 13):

$$P_c = P_{\text{depth}_c} \bullet P_{\text{temp}_c} \bullet P_{\text{salinity}_c} \bullet P_{\substack{\text{primary} \\ \text{production}_c}} \bullet P_{\substack{\text{ice} \\ \text{concentration}_c}} \bullet P_{\substack{\text{land} \\ \text{distance}_c}} \tag{13}$$

An example of an occurrence probability layer is presented subsequently for the silky shark (*C. falciformis*) in Figure 14. The occurrence probability values for the specific geographical dimension of the Indian Oceanic EEZ for this species were acquired through excision from a larger AquaMaps global distribution map. In the figure, grid values may fall between 0-1, which are represented simultaneously by a color and transparency gradient on the cells in question.

Via the inclusion of occurrence probability, fishing effort distribution data is weighted against a factor that may act as proxy value for abundance or density at a subunit scale with the theoretical backing of this linkage assumption being based on fairly foundational homeostatic/ecological principles within biology, stating that the numerical densities of all faunas will drop off the further they are situated away from optimal habitat and environmental conditions, outside of evolutionary time of course (Pulliam, 2000; Sagarin, Gaines, & Gaylord, 2006). Incorporation of a habitat preference dimension is intended to increase accuracy and validity of geographically couched species distribution computations, and although unimplemented in the original publication, such a data layer was specifically noted as a desirable methodological enhancement by Zhou et al. in original discussions of their SAFE equations (Zhou et al., 2011; Zhou & Fuller, 2011; Zhou, Fuller, & Daily, 2012).

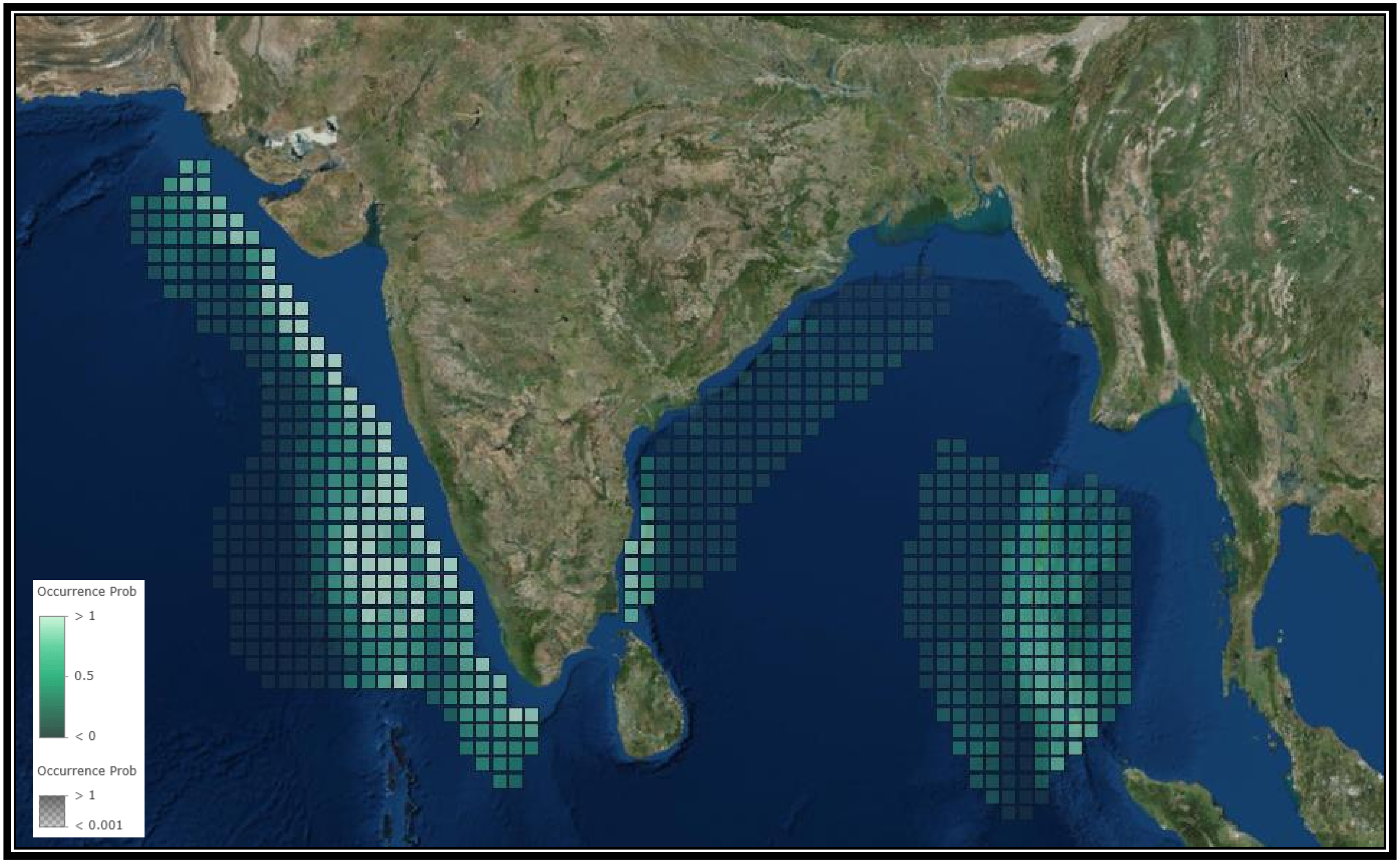


Figure 14. Silky Shark (*C. falciformis*) grid-wise (0.5° Lat × 0.5° Long) occurrence probability map / layer for India's oceanic EEZ.

Values for Fisheries Jurisdiction Area (FJA) Layer (L_2)

The values in cells for the Fishing Jurisdiction Area can take the values of $\emptyset$ (0.00 for simplicity), 0.25, 0.5, 0.75, 1.0. The values <1 purely arise from the process of delimitating the curved FJA Area within the context of a cell-based area construct. Where the values do not equal 1, a grid was cleaved via the FJA demarcating boundary line, with new values equal to the proportion of cell retained within the FJA at the resolution of quarter cells (i.e. [0.25° Lat × 0.25° Long]). The FJA within the context of this study is homologous with the oceanic sector of the Indian EEZ (Figure 15b; cf. Figure 15a). The oceanic sector, and thus the FJA, is somewhat geographically unique, as the Indian EEZ claim is comprised of two, large—though non-contiguous—marine areas, namely the mainland EEZ the EEZ surrounding the Andaman & Nicobar Islands, which are collectively a Union territory of India (direct administration by central Union Government, as opposed to a state government). To note, at least within this study, any textual reference to the EEZ, oceanic or otherwise, de facto refers to the entire claim (mainland and A&N waters) unless otherwise mentioned (or situationally implied), which however is not uncommon. All considered, the territorial demarcation of the oceanic EEZ regarding the mainland component is defined by two boundaries, an outer and inner. The outer-boundary is comprised of the outer boarder of the mainland EEZ and the inner-boundary is characterized as the topographically evident transition ridge from continental shelf to initial drop-off.

Figure 15a. Total Indian EEZ (mainland and A&N). Darker blue polygons.

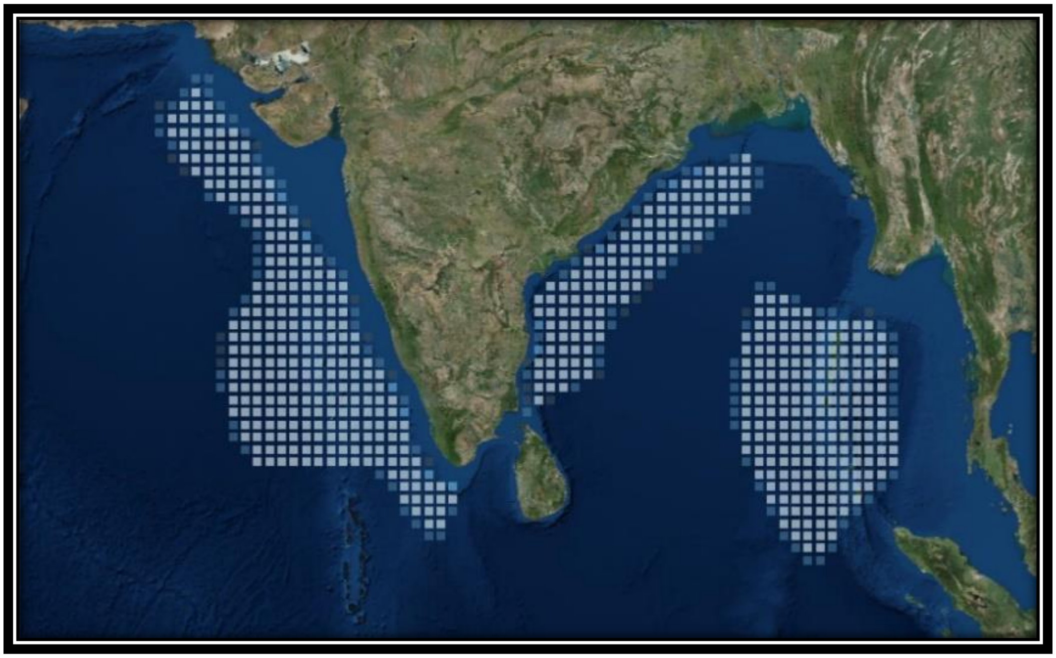


Figure 15b. Oceanic sector of Indian EEZ (or FJA). The area occupied by white and other colored grids represents the oceanic sector, which is superimposed on top of the darker blue area representing the total EEZ area (as seen here as well as unobstructed in the previous Figure [15a]). Note area difference b/w total Indian EEZ and oceanic FJA via lack of shelf area or "coastal" inclusion.

Regarding the Andaman & Nicobar Islands EEZ, given that it is an accretionary ridge archipelago and not a large continental plate (Bandopadhyay & Carter, 2017), its insular shelves take up a much smaller proportional footprint in comparison to its mainland counterpart within the context of its total EEZ. Additionally, the lack of shelf and concomitant coastal area results in a depth drop-off to 200 m (that depth being another numerical designation of transition from inshore to oceanic) occurring much closer to shore (Rodolfo, 1969). Although an areal value of the inshore/insular shelf area was found for the A&N Islands, its relevance in areal terms is also quite small (maybe between 5-7%), so in effect the oceanic sector of the A&N EEZ is defined alternatively as the remaining 93-95% of the EEZ claim area—that is, the area exteriorly concentric to the small island clusters and their modest insular shelfs, beyond which the oceanic zone extends unimpeded to the formal outer bounds of the EEZ perimeter.

Values for Longline Effort Distribution Layer (L_3)

The values populating the cells within this layer—that is, LL fishing effort distribution by catch station—contain the same area-wise information conveyed within FJA cell values. Similarly, the value is equal to the proportion overlap of a grid by catch station effort area to the resolution of a quarter cell and thus the geographic area value of effort in the cell. The method by which longline fishing station coordinates were converted into area values in occupied cells is outlined subsequently.

Unlike the derivation of the value of FJA, which was essentially accomplished by counting the number of grids and partial grids which approximate the irregular and curved area of the shape of the boundary of the oceanic EEZ, a unique method was utilized in the determination of geographic area of longline impact in any given cell, the array of which would populate the (L_3) layer.

Obtaining a valid stream of reasonably robust and temporally relevant data sets was quite difficult. However, a sufficient workaround was eventually designed (Figure 16 & Figure 17). Returning to the description of data acquisition difficulties, only one temporally relevant data product servicing the desired model inputs (specifically the area-wise distribution of LL gear effort) was ultimately identified in the literature. These data products assumed the form of scale-proportional map images with instances of recorded LL effort (via fishing stations) represented as geospatial points, the graphical locations of these points were of course equivalent to their appropriate Lat° × Long° geographical address on said map. These projections (Figure 16) were published annually for years 2010-2014 within respective status reports made by the agency of the Fisheries Survey of India (FSI) to the Working Party on Tropical Tunas (WPTT), a focal node within the IOTC. Sources include the following reports: Vijayakumaran & Varghese, 2011[IOTC-2011-SC14]; Vijayakumaran & Varghese, 2012 [IOTC-2012-SC15]; Premchand et al., 2013 [IOTC-2013-SC16-NR09]; Premchand et al., 2014 [IOTC-2014-SC17-NR09]; Premchand et al., 2015 [IOTC-2015-SC18-NR09]. Grid-wise area values transformed from fishing station location points were used to populate values for this layer. Map points represent longline fishing stations by both FSI longline survey fleets as well as by the commercial longline vessels in the IOTC vessel registry (Sijo P. Varghese, personal communication, 7 August 2017).

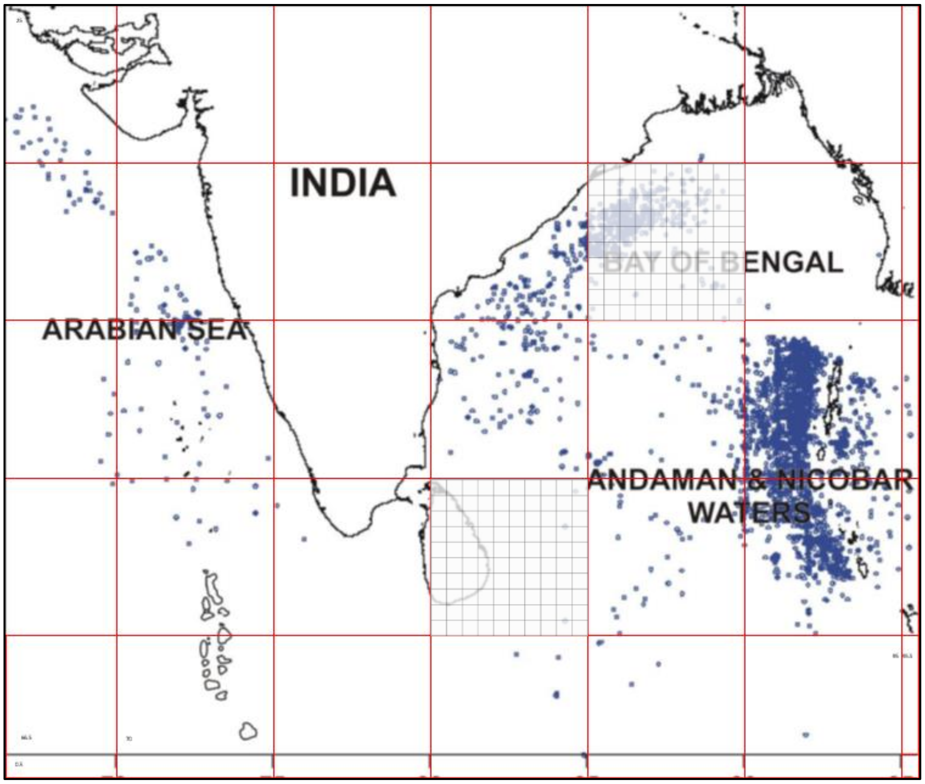


Figure 16. 2012 Oceanic longline fishing effort distribution by fishing station. Projection map as published in (IOTC-2013-SC16-NR09). Some additions have been made in terms of superimposing clearly visible latitude and longitude lines. Red lines represent [5.0° Lat × 5.0° Long] reference cells, while a few of those have been further subdivided to operative [0.5° Lat × 0.5° Long] level of resolution for the purpose of demonstration; [0.5° Lat × 0.5° Long] cell resolution was used exclusively for all spatial construct utilized in this study.

Although the data were presented in a map format within the context of the publications drafted for the IOTC WPTT (Figure 16), the raw numerical data or exact GIS records were explicitly not available for public review de jure (Sijo P. Varghese, personal communication, 7 August 2017). Therefore, data had to extracted from the suite of available graphical representations of the effort distribution, which produced the following conventions for delimiting effort area values at a grid resolution of 0.5° Lat ×

0.5° Long through the arrangements of provided fishing station positions. The per-cell value allocation process is defined in Figure 17 below.

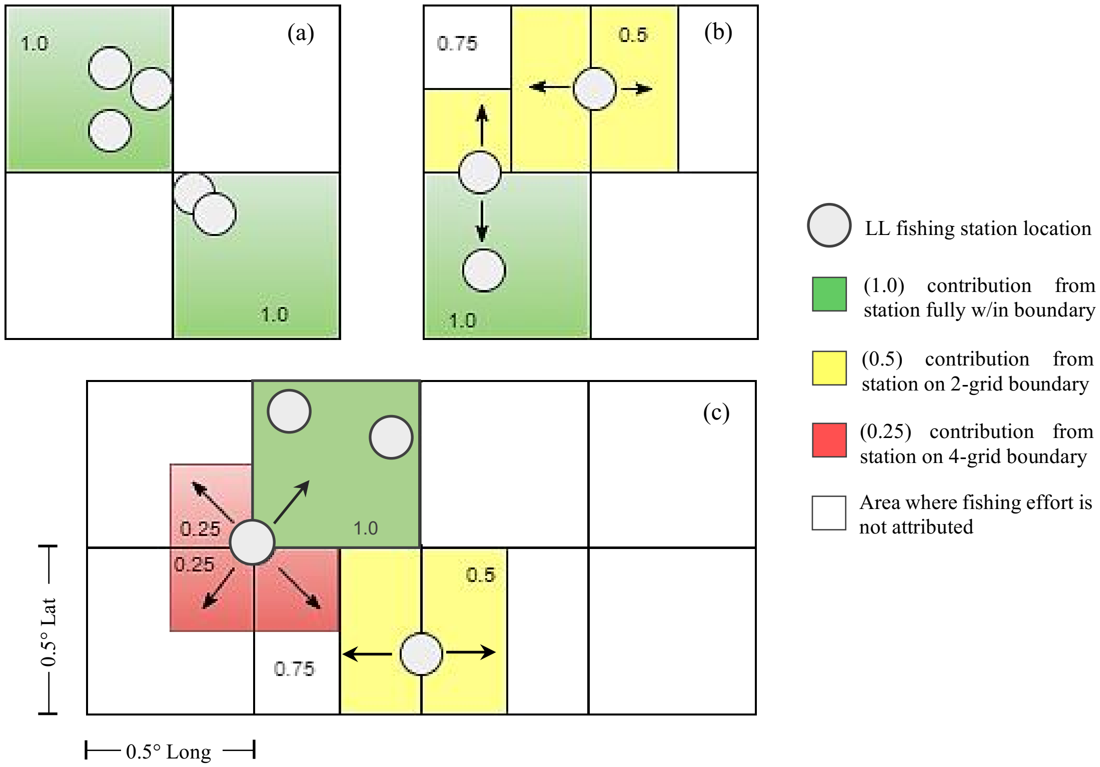


Figure 17. Grid-wise (i.e. cell-wise) value allocation criteria of longline effort area distribution via fishing station point values. Assume all square subdivisions represent a standard geospatial grid unit of 0.5°Lat. × 0.5° Long. each.

(a) Any grid unit fully housing at least one fishing station was given a full value of 1.0. No value greater than 1.0 in a cell is possible. As is shown in both the upper-left and bottom-right grids of (a), >1 fishing station is present in each, yet they still only receive a maximum value of 1.0.

(b) Any grid having no other stations beside straddling stations (other than in 4-way grid corners), is given the value of 0.5 distributed pole-wise parallel to the boundary grid line. Restated, the fishing station straddling the boundary line in effect broadcasts a 0.5 value to each of the two adjacent cells comprising the boundary line on which it sits. As one can see, this situation may happen with respect to multiple boundaries of a single cell; a cumulative effect is therefore possible resulting in a value of 0.75 when there is overlap from straddling stations located on perpendicular grid boundaries, as in the upper-left grid of (b).

(c) Points located on a 4-way Lat. × Long. grid intersection spread their value quarter-wise to each of the abutting squares. Where dense effort has been located, this superposition of effort can mostly be discounted as the cells frequently already contains a maximum 1.0 configuration (as in grid x_2, y_2 in (c)); however, at the fringes of geographical effort distribution, it becomes more common, and due to this frequency, a special construct and rule-based value allocation system was developed. In such cases, additive combinations can also occur, as in the case of grid [x_2, y_1] in (c)—that particular square's value is 0.75 due to two partial edge incursions into the grid.

It should be noted that even with these exacting partial spatial designation schemes, the appropriate prescription of cell value through station points can still be ambiguous and is privy to a somewhat rapid real time judgement pertaining to classification, especially when done manually in the context of thousands of cells, as was the case in this study. On a point-by-point basis, there may be disagreement at many points based purely on the observer's judgement and even among repeat evaluations performed by the same observer on the same map. Though, on the whole, it is assumed that accuracy may still be well maintained via this method and system of designation. A second source of error outside of simple misclassification arises from a potential frame shift error, which is potentially more drastic. This may happen intrinsically via the warping of data as it is changed across digital formats and/or geographic projection schemes (i.e. planar rendering vs. that of a true globe) or from accidental manual movements of the layers by the user between uses. Small frame shifts result in basic data loss, where boundary points are shifted wholesale out of the jurisdiction in question. One final counterpoint is that fortunately, since the region is very close to the equator, warping and change of scale (distortion) across projection types is not very severe.

Overall, the best practice would have been to secure the tabular data to remove initial ambiguity and/or inter-observational error; however, given that such a form of recourse not within the realm of possibility, the data extraction technique presented was determined to be a viable alternative. Once values have been successfully negotiated for all interacting grids, as gleaned initially from the yearly FSI reports to the IOTC WPTT, annual [0.5° Lat × 0.5° Long] grid maps can be produced, acting as necessary L_3 spatial layers. L_3 or longline effort distribution layers from 2010–2014 are shown in Figures 18 [a–e], which represent grid-wise (0.5° Lat × 0.5° Long) longline effort distribution (of fishing stations) by year in India's oceanic EEZ. Values from 0–1 correspond to proportion of cell spatial overlap by longlining station effort in a specific year. Sources of station locations are drawn from the national reports drafted by the Fisheries Survey of India for submission to the IOTC Working Party on Tropical Tunas. Map legend symbols are simply visual stand-ins for the cell values they represent, and thus all symbols designate the coordinates of affected marine area. As cells subject to fishing effort can take values of .25, .5, .75 or 1.0, based upon amount of cell overlap when fishing stations were defined along cell boundary conditions, the four different colors for a specific symbol within an individual year-layer correspond to these values, respectively; there is no meaning between same color or shapes should they repeat in a different year layer.

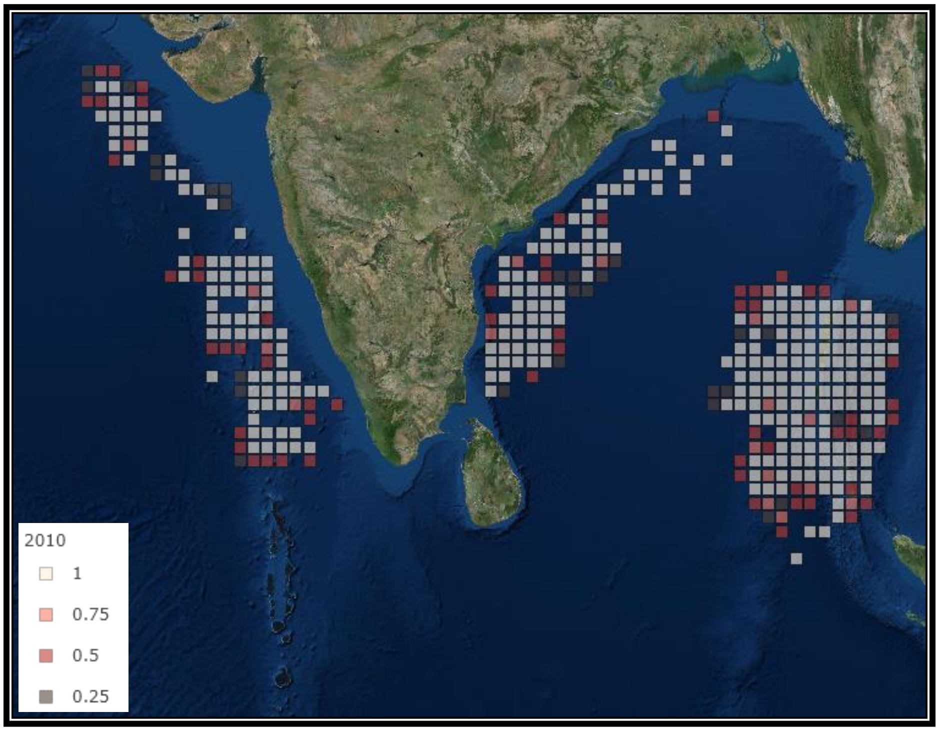


Figure 18a. Longline effort distribution for 2010.

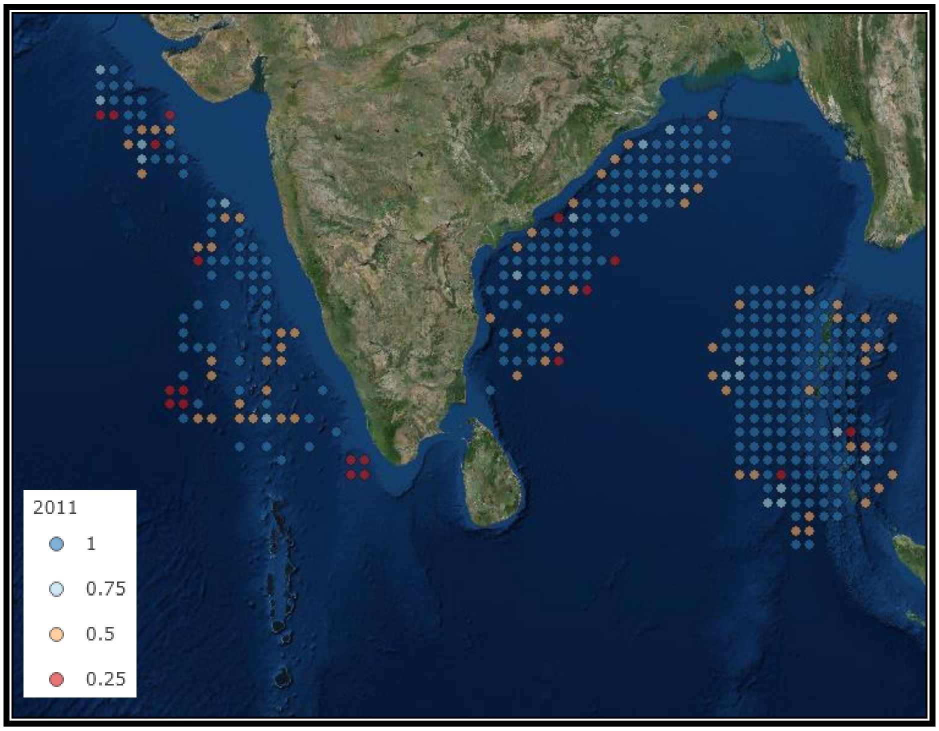


Figure 18b. Longline effort distribution for 2011.

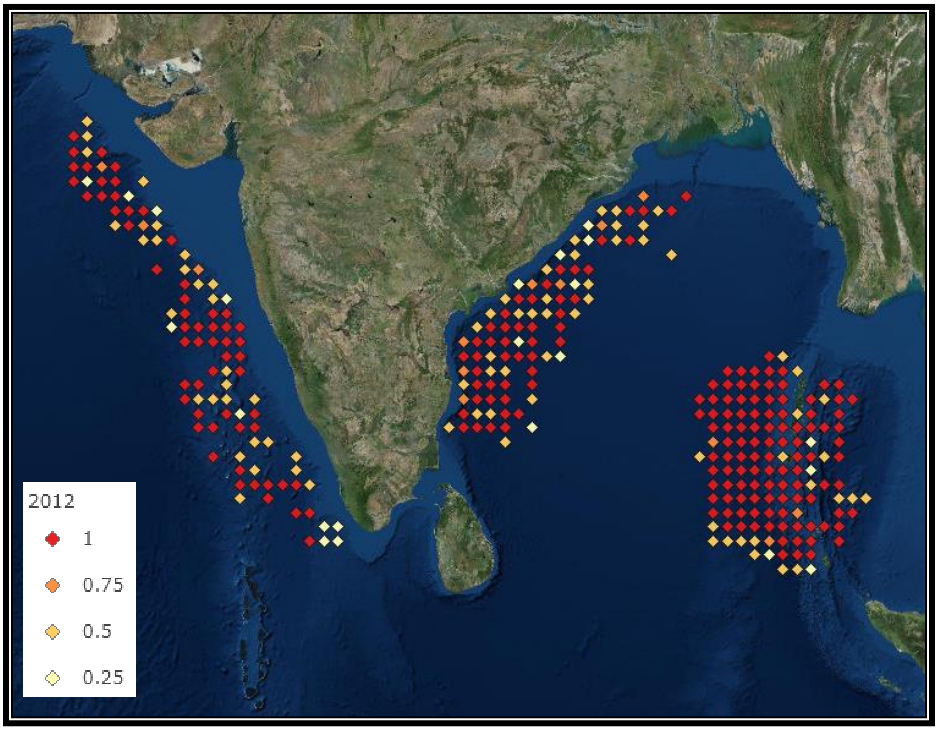


Figure 18c. Longline effort distribution for 2012.

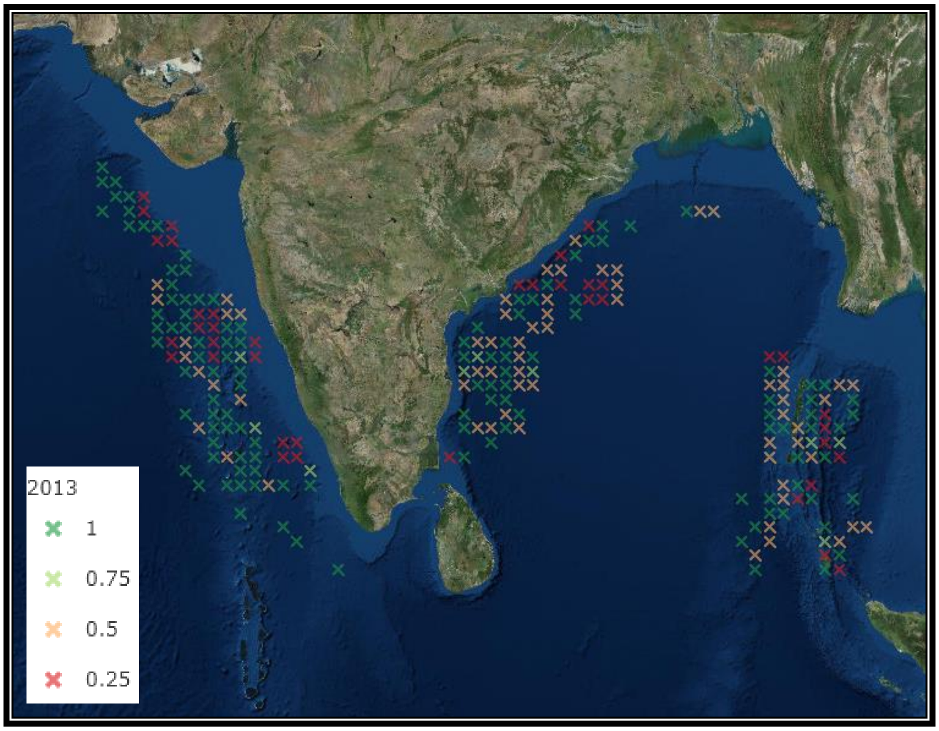


Figure 18d. Longline effort distribution for 2013.

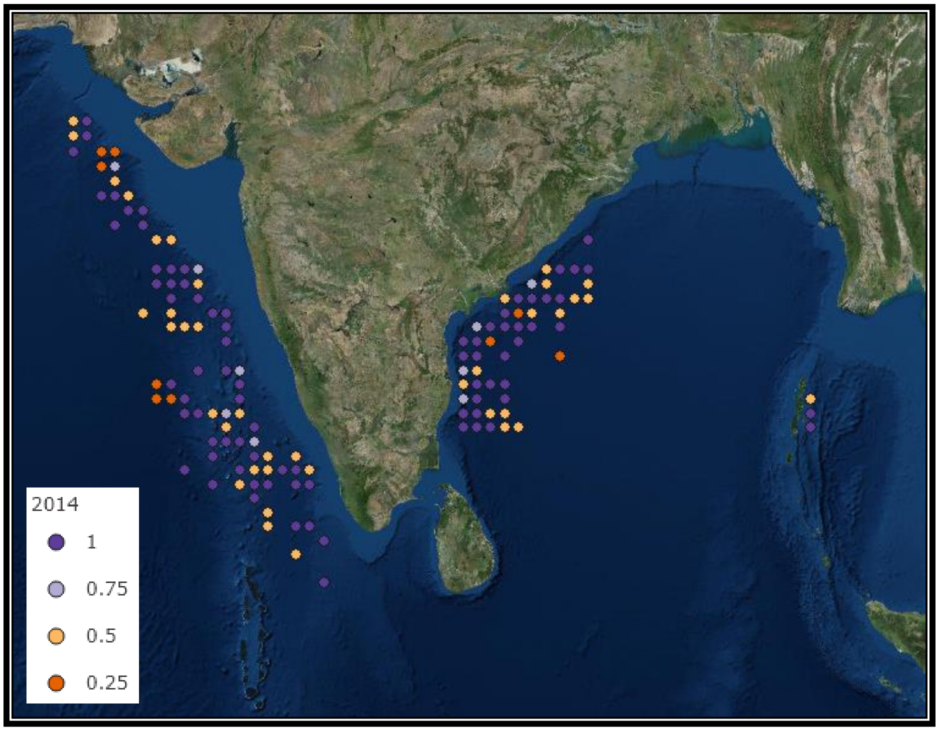
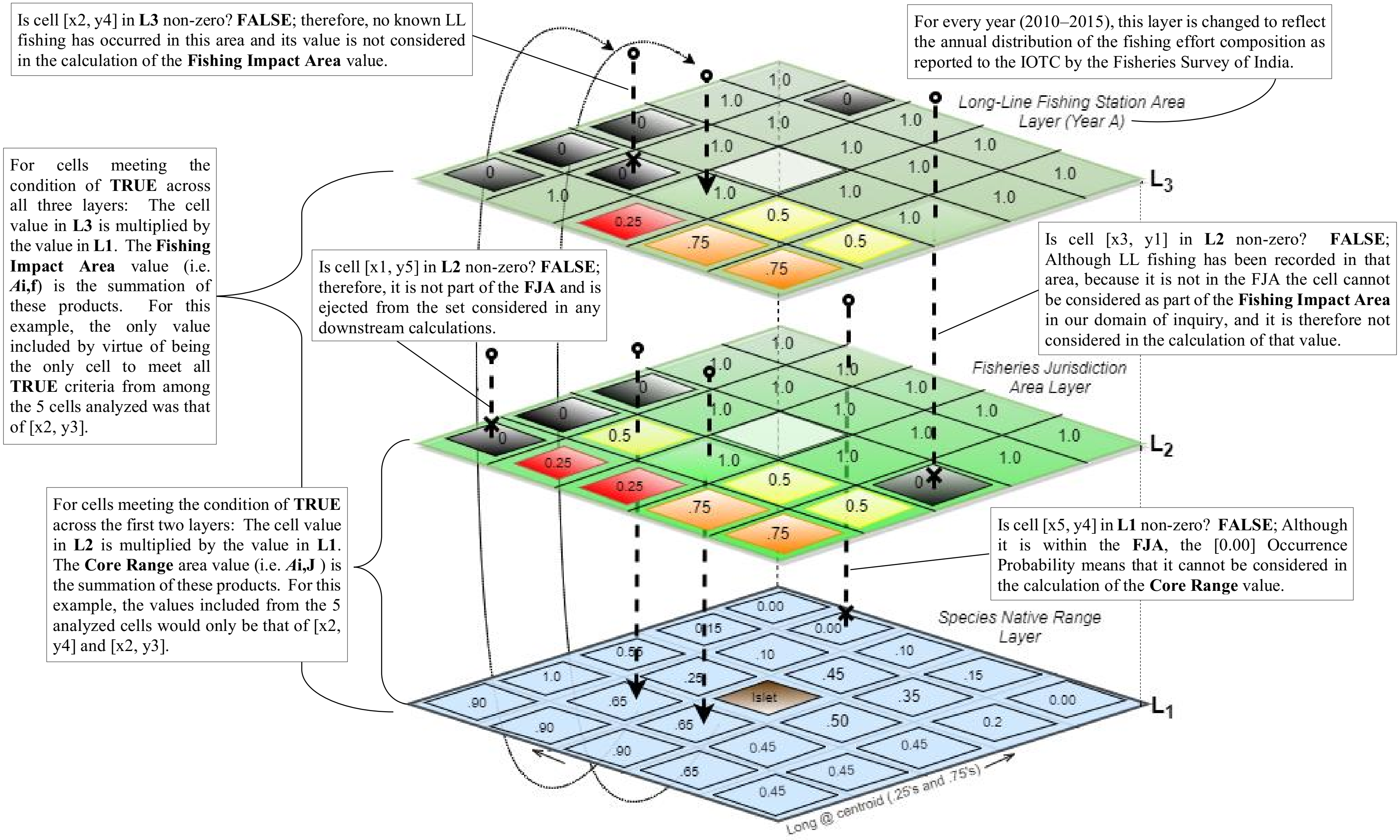


Figure 18e. Longline effort distribution for 2014.

Spatial Layer Synthesis for the Calculation of $A_{i,J}$ & $A_{i,f}$

The mathematical relationship among the three spatial layers (L_1, L_2, L_3) is the manner by which $A_{i,J}$ (core range/habitat distribution) and $A_{i,f}$ (long-line effort distribution) may be derived. The way the spatial layers interact and produce outcomes is actually more intuitive than has likely been communicated up to this point, but it is a degree more involved than that which was outlined by Zhou et al. (2011) via the incorporation of the per-cell Occurrence Probability data dimension (Kaschner et al., 2016 [Aquamaps.org]). Therefore, a graphical representation is useful in this regard and is presented in Figure 19. The subsequent representation, although a toy model, really exhibits no fundamental difference as it pertains to the processes exercised in the context of the Indian Oceanic fishery under scrutiny, albeit a very large difference in scales.

However, rapid escalation of scale with increasing geographical purview, increased cell resolution, and species numbers (or any combination thereof) was less of an operational burden than would be initially thought (though increasingly involved data organization structure does become necessary). This was due to the nearly exact homology between grid-based spatial layers and basic operation of spreadsheets. Excel with some specific VBA solutions were heavily utilized. More tailored geographical software was also incorporated such as ArcGIS Pro (ESRI, 2017). Although they did afford some additional capacities, the ease of use of Excel often won the day for pure bulk operations, though for presentation graphics ArcGIS Pro was certainly better equipped, with a number of map products created therein used at various points in the within the paper (Figure 14; Figures 15 [a,b]; Figures 18 [a-e]).



Is cell [x2, y4] in **L3** non-zero? **FALSE**; therefore, no known LL fishing has occurred in this area and its value is not considered in the calculation of the **Fishing Impact Area** value.

For every year (2010–2015), this layer is changed to reflect the annual distribution of the fishing effort composition as reported to the IOTC by the Fisheries Survey of India.

For cells meeting the condition of **TRUE** across all three layers: The cell value in **L3** is multiplied by the value in **L1**. The **Fishing Impact Area** value (i.e. ***A*i,f**) is the summation of these products. For this example, the only value included by virtue of being the only cell to meet all **TRUE** criteria from among the 5 cells analyzed was that of [x2, y3].

Is cell [x1, y5] in **L2** non-zero? **FALSE**; therefore, it is not part of the **FJA** and is ejected from the set considered in any downstream calculations.

Is cell [x3, y1] in **L2** non-zero? **FALSE**; Although LL fishing has been recorded in that area, because it is not in the FJA the cell cannot be considered as part of the **Fishing Impact Area** in our domain of inquiry, and it is therefore not considered in the calculation of that value.

For cells meeting the condition of **TRUE** across the first two layers: The cell value in **L2** is multiplied by the value in **L1**. The **Core Range** area value (i.e. ***A*i,J**) is the summation of these products. For this example, the values included from the 5 analyzed cells would only be that of [x2, y4] and [x2, y3].

Is cell [x5, y4] in **L1** non-zero? **FALSE**; Although it is within the **FJA**, the [0.00] Occurrence Probability means that it cannot be considered in the calculation of the **Core Range** value.

Figure 19. Spatial layer relationship for derivation of $A_{i,J}$ and $A_{i,f}$: toy example (by author).

In terms of basic tropes of interpretation of the graphical model (Figure 19), downward arrows represent the order of operation when linking values across layers (though not always correctly, as incompatible setups were used for the purpose of example, though marked accordingly). The cell values were picked for the toy example to demonstrate the full range of possible values for cells in a specific layer, or at least to the maximum extent feasible. Otherwise, most of the components are labeled for clarity.

Following, the graphical representation, a mathematical proof has been designed for full due diligence and possible replicability; however the binary gatekeeping mechanism which defines the possibility to progress through downstream layers and coupled operations when eligible is not very well served by standard algebraic concepts, so a somewhat esoteric scheme was devised which mingles Boolean (on/off) steps within a sequential and "permission based" set of algebraic operations, permission being granted through the clearance of conditional Boolean checks. The verbal, conceptual demonstration of this process was used in describing layer relationships in the graphical model (Figure 19); though, codification in this procedure into a mathematical framework was a bit more challenging.

Proof for the Derivation of $A_{\mathrm{i,J}}$ & $A_{\mathrm{i,f}}$ Via Sequential Interaction Among Value Populated Cells of Spatial Layers (Proof 2)

A) To Determine value of Core Range (or $A_{\mathrm{i,J}}$) for i^{th} species:

Such that,

If $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2} \neq 0$, then $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2}$ is in the FJA; $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2} \Rightarrow$ Boolean x

If $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1} \neq 0$, then $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1}$ has a non-trivial P_c for $\mathrm{species}_i$; $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1} \Longrightarrow$ Boolean y

If $x \wedge y =$ True, then multiply value of $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2} \bullet \mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1}$

$$\therefore \sum_{i=1}^{n} \mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2} \cdot \mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1} = \text{Core Range (or } A_{\mathrm{i,J}}) \qquad \blacksquare \qquad (14)$$

B) To Determine value of Fishing Impact Area (or $A_{i,\mathrm{f}}$) for i^{th} species:

Such that,

If $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2} \neq 0$, then $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2}$ is in the FJA; $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_2} \Longrightarrow$ Boolean x

If $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1} \neq 0$, then $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1}$ has a non-trivial P_c for $\mathrm{species}_i$; $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1} \Longrightarrow$ Boolean y

If $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_3} \neq 0$, then $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_3}$ has experienced LL fishing ; $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_3} \Longrightarrow$ Boolean z

If $x \wedge y \wedge z =$ True, then multiply value of $\mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_3} \bullet \mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1}$

$$\therefore \sum_{i=1}^{n} \mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_3} \cdot \mathrm{Cell}_{[x_i,y_i]}^{\mathrm{L}_1} = \text{Fishing Impact Area (or } A_{\mathrm{i,f}}) \qquad \blacksquare \qquad (15)$$

Summary of Pre-Model Calculations & Data Collection

The numerical results included herein are results of the procedures carried out in this entire chapter. These results are carried over to chapter III and act as the value-based data declaration, or the literal “observations” that will seed the Bayesian hierarchical model. The first of the two subsequent tables (Table 8) covers data that were, for the most part, pulled from key sources, potentially with some minimal transformational step, and thus titled ‘acquisition’. The Data Scaling Constant (sometimes referred to as the Area Constant within this study as well), is included in this table. Its derivation and relevance are outlined in detail in a prior section in this chapter (see section “Deriving Regional Fishing Mortality (F) Values for Fishery Dominant Target Species: *Thunnus albacares*”), but it is generally affiliated with the process of deriving F^{YFT} for yellowfin tuna in the Oceanic EEZ based upon F^{YFT} from the greater IOTC competence area. It is simply the ratio of the parent area to child area in km^2 or (A_{IOTC} / A_{EEZ}). It is defined as a constant (non-stochastic) value and is active in functions couched within the Bayesian hierarchical model for the derivation of F^{ShK} in essentially the same formula and context as presented initially.

Table 9 outlines the values of $A_{i,j}$ and $A_{i,f}$, as well as the values of q_i^h, q_i^λ, and PcM_i. Due to the strictly computational basis of furnishing these novel values, as opposed to directly pulling the values from the literature (as is mostly the case in the former table), they have been termed ‘operations.’ Although significant components of the mathematical and value production scheme of the project, they are not results in the classic sense but significant along the stepwise procedural route and may be of value in their own right. The pre-model values not included in this table are the pre-model derivation of F for every species, the process and rationale of which are covered in the upcoming Chapter III (the values however are not published in this thesis), nor are the pre-model values for F_{msm}, F_{lim}, F_{crash} and M. The latter four values are framed in detail in their designated chapter (IV); however, pre-model values are published in Chapter IV & Ancillary Appendix 2.

Table 8. Summary table of values for all pre-model data acquisitions.

	Value for Year				
Variable	2010	2011	2012	2013	2014
IOTC Competence Area					
Total YFT (C)	301738	329305	400501	405050	408511
Total YFT (F)	0.12835	0.1208	0.13741	0.15855	0.18573
Oceanic EEZ of India					
LL YFT (C) [a]					
Abdussamad et al. (2012a, 2012b)	22616.22	25005.38	N/A	N/A	N/A
Hornby et al. (2015a, 2015b)	22575.26	21070.94	N/A	N/A	N/A
India's National [b] Reports to IOTC-SC (2010–2015)	8892.77	8581.61	12095.76	15433.32	17676.92
Area Scaling Constant [c]	27.12606227				

Note. Catch (C) is in tonnes (t); (F) = Fishing Mortality; IOTC = Indian Ocean Tuna Commission; YFT = Yellowfin Tuna (*Thunnus albacares*); LL = Long-line; SC = Scientific Committee; FSI = Fisheries Survey of India. "Total" in this context refers to the outcome of all gears combined. N/A values are years not represented within the scope of specific publications.

[a] Longline *only* YFT catch with respect to different studies' estimates thereof in the Indian Oceanic EEZ, the subsequent numbers *do not* represent a total of all gears.

[b] In total, five separate annual reports submitted by the Fisheries Survey of India to the Scientific Committee of the Indian Ocean Tuna Commission inform this row of data; (Various Authors, 2010–'15)

[c] For derivation of the explicit value of the "Area Scaling Constant," see Proof 1 (Chapter II).

Table 9. Summary table of values for all pre-model operations $\{q_i^h, q_i^\lambda, PcM_i, A_{i,J}, A_{i,f}\}$.

Sp. No	Core Habitat ($A_{i,J}$) [b]	$A_{i,f}$ [b] $A_{i,f} / A_{i,J}$					q_i^h	q_i^λ	PcM_i
		2010	2011	2012	2013	2014	Est. range[c]	Est. range[c]	Est. range[c]
∅ [a]	520.23	256.83	244.91	205.51	133.73	90.78	0.999	0.999	0.999
	$A_{i,J} / A_{i,f}$ →	2.03	1.05	1.19	1.54	1.47	-	-	-
1	86.47	54.31	42.19	39.95	35.26	15.79	0.999	0.246	0.875
	$A_{i,f} / A_{i,J}$ →	0.63	0.49	0.46	0.41	0.18	-	-	-
2	571.87	288.74	289.39	234.75	149.61	99.19	0.999	0.996	0.984
		0.50	0.51	0.41	0.26	0.17	-	-	-
3	251.45	141.58	120.97	111.91	80.99	51.79	0.999	0.925	0.99
		0.56	0.48	0.45	0.32	0.21	-	-	-
4	529.86	261.17	249.12	209.01	135.93	91.94	0.999	0.939	0.974
		0.49	0.47	0.39	0.26	0.17	-	-	-
5	74.86	45.28	34.40	33.09	29.62	13.63	0.999	0.521	0.903
		0.60	0.46	0.44	0.40	0.18	-	-	-
6	68.42	39.72	31.16	29.57	25.84	11.92	0.999	0.245	0.999
		0.58	0.46	0.43	0.38	0.17	-	-	-
7	409.66	199.16	203.21	165.35	106.72	73.93	0.999	0.562	0.18
		0.49	0.50	0.40	0.26	0.18	-	-	-
8	126.56	80.29	67.70	62.95	53.88	22.34	M	M	H
		0.63	0.53	0.50	0.43	0.18	L–MH	L–H	M–H
9	220.16	89.82	77.40	71.70	55.15	43.59	MH	H	H
		0.41	0.35	0.33	0.25	0.20	M–H	L–H	M–H
10	435.38	208.17	187.52	164.15	108.07	74.51	0.999	0.622	0.999
		0.48	0.43	0.38	0.25	0.17	-	-	-
11	521.35	255.91	245.43	205.68	133.78	90.60	0.999	0.97	0.994
		0.49	0.47	0.39	0.26	0.17	-	-	-
12	36.86	13.65	11.90	12.97	4.72	7.74	0.999	0.6	0.992
		0.37	0.32	0.35	0.13	0.21	-	-	-
13	283.58	108.75	88.99	80.99	69.63	58.96	0.999	0.997	0.999
		0.38	0.31	0.29	0.25	0.21	-	-	-
14	514.06	256.45	254.60	208.55	132.72	89.33	0.999	0.997	0.997
		0.50	0.50	0.41	0.26	0.17	-	-	-
15	59.60	40.25	28.86	25.91	22.61	10.03	MH	H	H
		0.68	0.48	0.43	0.38	0.17	L–H	L–H	M–H
16	51.96	34.73	24.72	21.55	19.33	7.84	MH	H	H
		0.67	0.48	0.41	0.37	0.15	L–H	L–H	M–H

17	547.21	272.40	255.13	216.86	137.90	91.51	0.999	0.968	0.97
		0.50	0.47	0.40	0.25	0.17	-	-	-
18	71.58	43.31	31.55	31.12	29.17	13.40	MH	H	H
		0.61	0.44	0.43	0.41	0.19	L–H	L–H	M–H
19	17.03	4.47	0.95	4.01	4.74	3.31	MH	MH	H
		0.26	0.06	0.24	0.28	0.19	L–H	L–H	M–H
20	95.92	58.61	47.99	46.27	40.38	17.93	LM	MH	H
		0.61	0.50	0.48	0.42	0.19	L–MH	L–H	M–H
21	75.78	46.57	34.74	33.74	31.44	14.63	MH	H	H
		0.61	0.46	0.45	0.41	0.19	L–H	L–H	M–H
22	57.18	40.03	29.54	25.01	21.77	8.64	M	H	H
		0.70	0.52	0.44	0.38	0.15	L–H	L–H	M–H
23	65.90	44.68	32.55	29.57	24.94	11.02	MH	MH	H
		0.68	0.49	0.45	0.38	0.17	L–H	L–H	M–H
24	62.17	28.00	31.53	25.10	18.54	9.67	MH	MH	H
		0.45	0.51	0.40	0.30	0.16	L–H	L–H	M–H
25	28.70	9.34	4.42	5.74	8.69	5.68	0.999	0.172	0.999
		0.33	0.15	0.20	0.30	0.20	-	-	-
26	51.90	41.17	31.04	24.36	20.88	7.73	LM	MH	H
		0.79	0.60	0.47	0.40	0.15	L–H	L–H	M–H
27	51.98	36.62	26.27	22.62	19.90	8.05	MH	MH	H
		0.70	0.51	0.44	0.38	0.15	L–H	L–H	M–H
28	48.68	35.68	26.09	21.53	18.51	7.18	LM	H	H
		0.73	0.54	0.44	0.38	0.15	L–MH	L–H	M–H
29	22.50	11.81	8.15	8.52	9.37	5.41	M	H	H
		0.52	0.36	0.38	0.42	0.24	L–MH	L–H	M–H
30	55.01	36.75	26.45	23.14	20.93	8.66	M	MH	H
		0.67	0.48	0.42	0.38	0.16	L–MH	L–H	M–H
31	43.43	34.57	24.30	18.90	15.77	6.40	-	-	-
		0.80	0.56	0.44	0.36	0.15	-	-	-

Note. Risk Score Designations: **L** = Low (Risk) [0.333]; **LM** = Low-Medium [0.4995]; **M** = Medium [0.666]; **MH** = Medium-High [0.8325]; **H** = High [0.999]. The calculation for Pre-model (F) for corresponding species is not included in this table; however, a description and rationale of Pre-model (F) may be found in Ch. III. See Table 5 (in Ch. I) or Table 17 (Ch. V) for shark species number key (each shark species corresponds to an individual number, which is retained for every relevant table in the study to avoid the need to repeat names at every table).

[a] ∅ denotes the target species Yellowfin Tuna (*Thunnus albacares*) and its corresponding values utilized in the overarching fisheries equation, namely in the (ρ) sub-equation. For ∅, and for any target species in general, the value of ($A_{i,\,J} / A_{i,\,f}$) is given in the table, intentionally inverted, as this inverted relationship is utilized in the (ρ) sub-equation. For all other bycatch species in the table (shark species: 1-31), the value of ($A_{i,\,f} / A_{i,\,J}$) is given in standard form (i.e. not inverted) and represents the ratio of Fishing effort distribution to Core Habitat, which is a critical piece of information within this study.

[b] Areas in the variables of Core Range ($A_{\mathrm{i,\,J}}$) and fishing effort distribution ($A_{\mathrm{i,\,f}}$) are weighted by Occurrence Probability, so they are not exactly equal to maximum habitat area polygons. The values given are the number of [0.5° Latitude × 0.5° Longitude] grids, which are approximately equal to 2950 km^2 each.

[c] If catch mechanism variable values are not published as discrete values in pre-existing literature, then a credible risk range is derived. If the credible state of knowledge is really '0' information, or especially in the case of habitat ambiguity, the range may span low to high risk (**L**–**H**) without preference; the minimum possible score is (**L**) unless otherwise published. A precautionary, most probable value of this range is given as a singular 'point value'. The 'point value' is then used in the pre-model calculation of (F) (see Chapter III) and the risk score range is utilized in a different part of the analysis—the low and high range values are incorporated as the minimum and maximum [a, b] range parameter values on a corresponding uniform prior in the Bayesian model for the derivation of (F). If values are published for catch mechanism variables, then they are incorporated as a constant value for a corresponding beta parameter, rather than a uniform prior spanning the plausible range.

Chapter III

Methods, Part II: Bayesian Hierarchical Model for the Derivation of Shark Fishing Mortality (F)

Figure 20. Vishnu as the Fish Avatar, Matsya. Kangra, India. 1805 – 1815. Gouache on paper. Reproduction with the permission © 2017 University of Oxford - Ashmolean Museum.

Two separate Bayesian models were implemented for the derivation of different features. The first was a stochastic reprisal of the Zhou et al LL eq. for the purposes of deriving bycatch F for various shark species. The second was for the purpose of deriving biologically based management reference points (F_{msm}, F_{lim}, F_{crash}). The first model will be defined here in Chapter III and the second in Chapter IV. The methods of the model's construction, active components, and the conceptual basis for decisions are presented as they arise over the arc of this chapter.

Conceptual Overview of Bayesian Inference

Bayesian inference was historically referred to as "inverse probability" (Fienberg, 2006), since it makes it possible to answer questions about the probability of a phenomenon given the observed data. In contrast, in the traditional (or frequentist) branch of statistical inference, statements can only be made about the expected relative frequency of an outcome through repeated sampling within the same experiment (Pulkkinen, 2015).

A fundamental quality of Bayesian inference is that probability is rendered to exist only as a "subjective degree of belief" (DeFinetti, 1975). Thus, the results of Bayesian statistical inference are, by definition, considered subjective, depending on the agent conducting the analysis. Continuing this line of reasoning, two experts could easily produce differing results, even when they base their analysis on the same observed data, simply because their respective curation and incorporation of data and/or divergent interpretations of background knowledge were fundamentally different.

Within a Bayesian context, data, once observed, can be considered objective; however, when those data are interpreted and turned into knowledge about the subject studied, the objectivity cannot be maintained because of individual "degree of belief" choices inherent in establishing a prior probability or "prior knowledge" construct, which is a unique and defining feature of Bayesian statistics (Lindley & Phillips, 1976; Gelman, Carling, Stern, & Rubin, 2004). Although there has always been some couched critique of the intrinsic subjectivity of Bayesian statistics as a philosophical subversion of a central tenet of scientific understanding, i.e., core objectivity irrespective of observer (Galavotti, 2017), recently, however, things have settled down, and Bayesian methods are seen to be appropriate where one seeks to assess a probability about a 'state of the world'. Bayesian inference may even be said to be in the midst of an interdisciplinary renaissance regarding its scientific application (Howson & Urbach, 2006; McGrayne, 2011).

The fundamental stipulation of intrinsic subjectivity within Bayesian inference should not be considered a flaw of design, but rather a competing construct for describing the stochastic basis of observed phenomenon, with equal mathematical validity as frequentist statistics. In that vein, instead of striving for objectivity, it is more important to be able to justify the choices that have been made in an honest and transparent way, which is itself the basis of the validity of the result.

Bayesian inference is by definition a self-reinforcing mathematical construct, or learning process, where initial knowledge (i.e. prior distribution) is updated in context of recent information (i.e. the data, interpreted via likelihood function) and these together form an updated understanding regarding the phenomenon of interest (posterior distribution; Gelman et al., 2004).

Prior knowledge can range from highly specific to uninformative (Gelman et al., 2004). In a highly informative context, the prior may be expressly framed in terms of hard numerical limits (i.e. plausible minima or extrema values of a phenomenon) or specific design choices (reflecting an in depth prior understanding) regarding the probability distribution pattern a phenomenon of interest may be expected to express within the system of probabilities—given perhaps by robust, previously conducted studies—and transferred to the model via a highly tailored prior distribution (Vanpaemel, 2011). The prior distribution functions as the prior underlying state of knowledge about a system and is itself a subjective construct. In an uninformative context, prior knowledge may suggest that the data clusters around a central tendency such as a normal distribution, or even more uninformatively, may occupy any number on the infinite number line via a flat distribution (Gelman et al., 2004). However, if an actor has even a degree of knowledge which may posit that the prior value does not take any theoretically conceivable number (in the case of a flat distribution) and incorporates said knowledge, then final results may be mathematically improved via the incorporation of logical, entirely credible, yet fundamentally subjective knowledge.

Mathematically, this process is implemented first by setting up a joint probability distribution for the observable data, for example y, and parameters of interest, θ. This can be obtained as the product of the prior distribution, which describes the initial knowledge of the parameters (before the data were collected), and the conditional distribution of the observations given the parameters, representing the interpretation of data. The prior distribution is a probability distribution, and it is denoted by $p(\theta)$ or the probability of the parameters. The likelihood of the parameters given the data is proportional to the probability of the data given the parameters, $p(data|\theta)$ (Gelman et al. 2004). Thus, the joint probability distribution of the data and the parameters is (Equation 16):

$$p(\theta, data) = p(\theta)p(data|\theta) \tag{16}$$

Conditioning on the known y and using Bayes rule, the posterior distribution is furnished (Equation 17):

$$p(\theta|data) = \frac{p(\theta)p(data|\theta)}{p(data)}, \tag{17}$$

where $p(data) = \int p(\theta)p(data|\theta)d\theta$ is the integral over all possible values of θ. Thus, the posterior distribution expresses the new understanding about the phenomenon when the data, interpreted via the likelihood function, is combined with the initial knowledge. The prior distribution is a unique feature of statistical inference that only exists in the Bayesian framework. Its purpose is to be a mathematical vector for the incorporation of available background information, i.e. the knowledge one has before collecting new data. Because of the subjective nature of knowledge, the choice of a prior distribution may differ between actors as a valid subjective difference in their interpretation or level of knowledge of prior information.

Besides using expert knowledge, prior distributions can be formulated with any type of information coming from the literature (Cortés, 2002), various databases (Froese & Pauly (eds.), 2018), or previous Bayesian analyses (Raftery, Givens, & Zeh, 1995; Michielsens et al., 2008).

Bayesian Hierarchical Models

Bayesian hierarchical models offer an efficient way to jointly analyze data from various sources that essentially relate to the same phenomenon (Myers & Mertz, 1998; Punt, Smith, & Smith, 2011; Jiao, Cortés, Andrews, & Guo, 2011), especially in fisheries research. Hierarchical models are also a practical tool for formulating prior distributions (Michielsens et al., 2008). Suppose that an author has obtained a set of j studies of a fish stock; $j = 1, \ldots, n$; and that we wish to learn about the biological parameters $\theta = (\theta_1, \ldots, \theta_n)$ of that stock based upon different studies. The methodologies under which these studies were performed may have been different thus affecting the data sets collected, with component differences potentially including the sample area, time regime, sex or maturity focus of the analysis, or even potentially the theoretical basis of analysis and validity of outcomes, contingent upon different natural relationships to derive a biological value, or any combination of externalities such as those provided. This might imply that the values of θ are not identical between studies, but because they are from the same stock, it would be credible to assume that they have something in common. If no feature is known that would distinguish any of the $\theta_j's$ from any of the others, and their joint distribution is considered invariant to the permutation of the indices, it be may be functionally assumed the parameters $\theta_1, \ldots, \theta_n$ are exchangeable. The exchangeability assumption is a subjective decision that reflects the actor's subjective choice couched in the level of confidence held by the actor conducting the analysis. As with the predominant pattern, one actor may view a set of parameters as exchangeable, whereas another may not; the latter perhaps having more information and instead considering them as conditionally exchangeable. Conditionally exchangeable parameters are exchangeable in the residual variation, or that which remains after the relevant degree of variation has been explained with a covariate.

Seasonality is an example of a covariate, should one actor deem that time of year has a significant non-random influence on the value of the parameter of interest. Due to the assumption of exchangeability, each θ_j can be considered as a draw of an independent sample from the same prior distribution yet conditioned by a set of common hierarchical parameters ϕ (Equation 18):

$$p(\theta|\phi) = \prod_{j=1}^{n} p(\theta_j|\phi) \qquad (18)$$

As ϕ is not usually known, it will be given a prior distribution of $p(\phi)$. Data is linked to θ through a likelihood function $p(y|\theta)$. The model within this study specifically also mirrors a typology known as "evidence synthesis" which can be broadly described as making inference on a quantity from more than one dataset at the same time. If there are *N* datasets, each assumed to be generated by a different model, but with a parameter θ in common, then all the datasets simultaneously provide information about θ (Lunn, Jackson, Best, Thomas, & Spiegelhalter, 2012).

Directed Acyclic Graph & Formal Graphical Language

Acting as a homologue to symbolic mathematical notation, directed graphical models, also known as Bayesian Networks, depict the joint distribution of n random variables $\mathbf{X} = (X_1, \dots, X_d)$ by a directed acyclic graph in which each node *i*, denoting variable X_i, receives directed edges (arrows) from its set of parent nodes π_i. The semantics of a directed graphical models are such that that the joint distribution of **X** can be factored into the product of conditional distributions of each variable given its parents. That is, for each setting of the **x** variable **X** (Equation 19):

$$p(\mathbf{x}|\boldsymbol{\theta}) = \prod_{i=1}^{n} p(x_i|\mathbf{x}_{\pi_i}, \theta_i) \tag{19}$$

This factorization codifies the graphical intuition that X_i depends on its parents—given extant parents, X_i is therefore statistically independent of all other variables which are not descendants of X_i . The set of parameters controlling the conditional distribution which relates $\mathbf{X}_{\pi_i}$ to X_i is θ_i, while the set of all parameters in the graphical model is signified $\boldsymbol{\theta} = (\theta_1, \dots, \theta_d)$ (Ghahramani, 2002).

Directed Acyclic Graphs (DAGs) have been commonly and successfully utilized in the representation a wide class of statistical models and are especially well-suited to those subject to a high degree of relational complexity, such as multi-dimensional Bayesian Hierarchical Models (Jensen & Nielsen, 2007). Due to this, the inclusion of a DAG as the focal, representational apparatus of the Bayesian model(s) utilized within this study seemed to be sufficiently founded.

DAGs communicate the essential structure of the model without recourse to a large set of equations. This is achieved by abstraction: the details of distributional assumptions and deterministic relationships may be 'hidden' (Lunn, Thomas, Best, & Spiegelhalter, 2000; Lunn, Spiegelhalter, Thomas, & Best, 2009), though in this model both are given explicitly as a decision for improved understanding. In general, a DAG represents a series of conditional independence assumptions: for any node *v*, if the parents are known then no other nodes provide further information about *v*, except for descendants of *v* (Equation 20):

$$v \perp\!\!\!\perp \text{nondescendants}[v] \mid \text{parents}[v] \tag{20}$$

where $\perp\!\!\!\perp$ denotes "is conditionally independent of" (Spiegelhalter, Thomas, Best, & Lunn, 2003). The conditional independencies expressed through DAGs allow properties of the model to be derived even if no specific probabilistic form has been specified (Lauritzen, Dawid, Larsen, & Leimer, 1990; Whittaker, 1990; Spiegelhalter, Dawid, Lauritzen, & Cowell, 1993).

The directed acyclic graph (Figure 24) represents all quantities as nodes (labeled shapes) in a directed graph, in which arrows run unidirectionally to nodes from their direct ancestor or influence (or parents). A model of this design represents the assumption that, given its parent nodes pa[v], each node is independent of all other nodes in the graph except descendants of v (Spiegelhalter et al., 2003)—descendants meaning down-arrow connected nodes. The graphical decisions contained herein should be understood as adhering to a specific and formal graphical language which retains direct mathematic equivalency, if not notational equivalence, to otherwise standard-form, equation-based representations of the model. Fundamental components of the utilized graphical syntax are drawn primarily from those which are utilized in OpenBUGS software's graphical architecture, albeit with some additions (namely, color for additional categorical designations; notational complexity of node names, and specific shapes utilized). This allows for an expanded framework to identify in graphical terms categorical affiliations and other information that the author has deemed useful for viewer clarity, but otherwise retains reasonably mutual consistency and theoretically intuitive transferability between the two (that is, this study's DAG framework and that utilized by OpenBUGS). The syntax utilized is this study's DAG is described in full below:

Node shape. For any arbitrary model-*cum*-DAG portrayed within this study's formal graphical language, quantity representation is found in the form of nodes. Purely visually speaking, within the DAG they can be identified as shapes named in textual terms. By a fairly elegant scheme of categorical reduction and graphical abstraction, nodes are able to afford the total possible body of applicable mathematical and operational design available to Hierarchical Bayesian Models via the specific spatial arrangement of three possible graphical shapes—rectangles, probability distributions, and hexagons—which, in turn, correspond respectively to three mathematical modalities: a) Constants (i.e. constant nodes); b) Stochastic Nodes (i.e. probabilistic distributions of a named model parameter/observed data); or c) Deterministic/Logical Nodes (i.e. a model specific functional relationship among relevant nodes).

a) Constant Nodes (Rectangles)—Fixed values by design of the study, always founder nodes. Denoted by rectangles (Figure 21a).

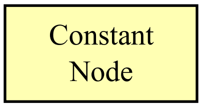


Figure 21a. Graphical depiction of rectangular constant node.

b) Stochastic Nodes (Probability distribution shapes)—Stochastic nodes represent a defined probabilistic distribution, either of unknown model components, and are defined as parameters, or as the distribution of observed data comprised of defined values. They may exist within any hierarchical placement from founder to final descendent, fulfilling various parent-child roles (sometimes simultaneously) among its affiliations, dependent on spatial placement, which is itself of course contingent on model design. Rephrased, stochastic nodes may be unobserved and hence be parameters, which may be unknown quantities underlying a model, observations on an individual case that are unobserved, say due to censoring, or simply missing data; alternatively, when specified, stochastic nodes may be observed, in which case they are data (Spiegelhalter, 2003). For overview of distribution shapes used, see Figure 21b below.

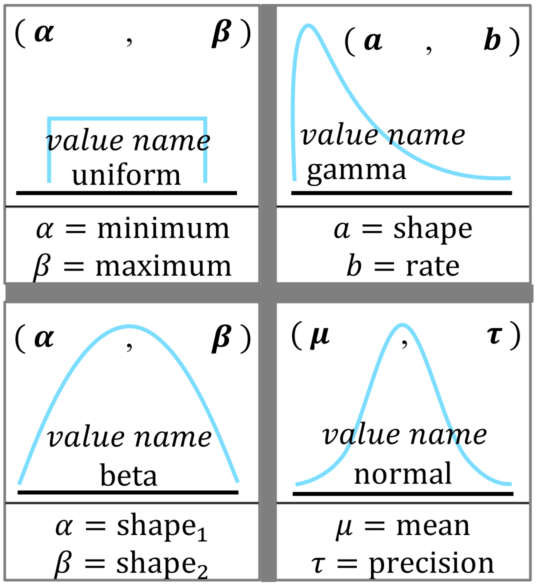


Figure 21b. Stochastic nodes' probability distribution shapes. The above template lists the full scope of distribution types (of which there are four: Uniform, Gamma, Beta, and Normal) operating within this study's various Bayesian hierarchical model. Furthermore, the key displays as how to interpret the corresponding numerical data presented w/ respect to stochastic nodes within the directed acyclic graphs.

c) Logical Nodes (Hexagons)—Logical functions of other nodes. Logical nodes (also called deterministic nodes) cannot be data. Logical nodes are always given as hexegons (Figure 21c). (NB. For the sake of clarity, the white coloring with respect to strictly logical nodes has nothing to doing with the categorical color scheme to be outlined subsequently; it was just chosen for internal uniformity but could theoretically be any color and is not a short hand for any sort of additional categorical significance).

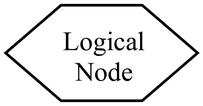


Figure 21c. Graphical depiction of hexagonal logical node.

Node color. The selection of color denotes special sub-categories among some types of nodes (namely stochastic and constant). The following color schemes are used to signify a specific type or convey additional information. The colors of (a) yellow and (b) white have identificatory significance with respect to different role classifications within stochastic and constant nodes (but not logical nodes, as just mentioned). Lastly, (c) red outlines are used to designate a node of significance:

a) Yellow—Denotes a node that operates as an observation node; both stochastic and constant nodes can function as observation nodes, albeit with obviously different properties (Figure 21d). Coincidentally, both are represented in our forthcoming model for F (see Figures 23–24); however, their respective inclusions are model contingent on a case-by-case basis. Stochastic nodes are specified to be the observation distributions which describe the random distribution of the imported observed data. Choosing a probability model for the data is analogous to the classic/frequentist approach of choosing a data model, which involves deciding on a probability distribution for the data as if the parameters were known (Glickman & van Dyk, 2007). In many standard cases, this simply takes the form of a normal distribution, but by no means ubiquitously. Constant nodes operating as observational nodes function similarly, as they directly incorporate relevant data obtained exterior to the model into its mathematical consideration; however, the fact that they are defined as constant, known entities not subject to stochastic tendencies position them as fundamentally different entities within the model, which are not subject to update as the model evolves over subsequent simulations. Within the context of WinBUGS software environment, quantities are specified to be data by giving them values in a data declaration step, defined in Table 11, which involves the creation and input of a predefined list of values.

b) White—Represents stochastic nodes with no additional categorical affiliations (Figure 21d). In other words, the default graphical representation of a stochastic node is a distribution shape with a white background, as opposed to the possible alternative of a yellow background when the node is acting as observed data.

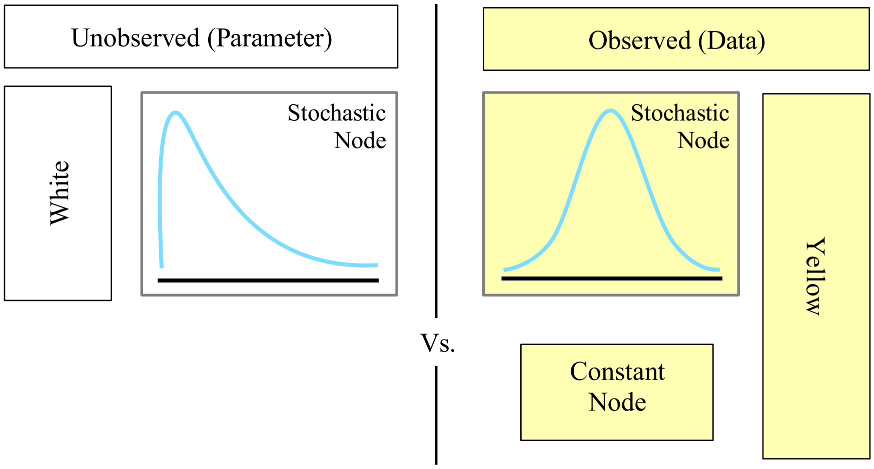


Figure 21d. Node color categorization (white vs. yellow). Distribution types (shapes) of stochastic nodes are arbitrary.

c) Red (Outline)—Within the DAG, red rings/red node outlines signal nodes of analytical significance within the broader model and study aims, whose marginal posteriors will be derived to obtain key output values, or in the case of deterministic nodes, the deterministic output of the defined logical function of its constituent terms, albeit when a term is a model parameter, the marginal posterior thereof operationally manipulated in the context of the defined logical function. This visual detail is, strictly speaking, purely for the purposes of guiding effective viewership of the model in relation to results derived therefrom and published later in the article and does not denote any specific mathematical connotations or formal qualities / relationships. Concisely, the red ring is equivalent in usage to highlighting or underlining an important phrase or text (Figure 21e).

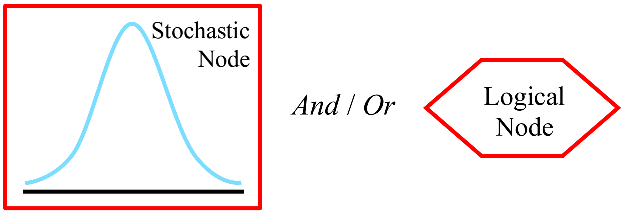


Figure 21e. Depiction of eligible nodes with red outline. Distribution type (shape) of stochastic node is arbitrary.

Object type. Aside from nodes, two other objects are contained within the formal graphical language of this study's DAGs, namely (a) Directed Links (arrows) and (b) Plates. Each of these two objects has significant constitutent features, sub-categoreies, and interpretive implications, details of which aare described subsequently:

a) Directed Links (i.e. Arrows), of which there are two types, namely (i) Thin Solid Arrows and (ii) Wide Triple-Stem Arrows (Figures 21f & 21g).

    i. Thin Solid Arrow—indicates a stochastic dependence between nodes.

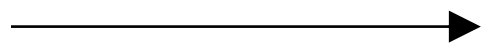


Figure 21f. Graphical depiction of thin solid arrow.

    ii. Wide Triple-Stem Arrow—indicates dependence based on logical function between nodes.

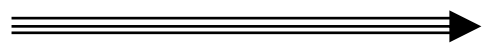


Figure 21g. Graphical depiction of wide triple-stem arrow.

b) Plates—Repeated parts of the graph can be represented using a "plate," taking the form of a large quadrilateral structure of arbitrary (but spatially relevant) size which lies underneath a specific arrangement of nodes (Figure 21h). The mathematical identity is equal to an index shared by all nodes lying above it over a given range of values or set of specific categories which may be sorted by proxy via a straightforward numerical designation (e.g., $F_{msm}=1$, $F_{lim}=2$, $F_{crash}=3$). The stacking of plates is completely possible, with, in theory, no requisite limit. Increasing plates increases the hierarchical levels and complexity of the model, but obviously such a feature is implemented in no arbitrary manner; rather, it is contingent upon the exact requirements of the source model.

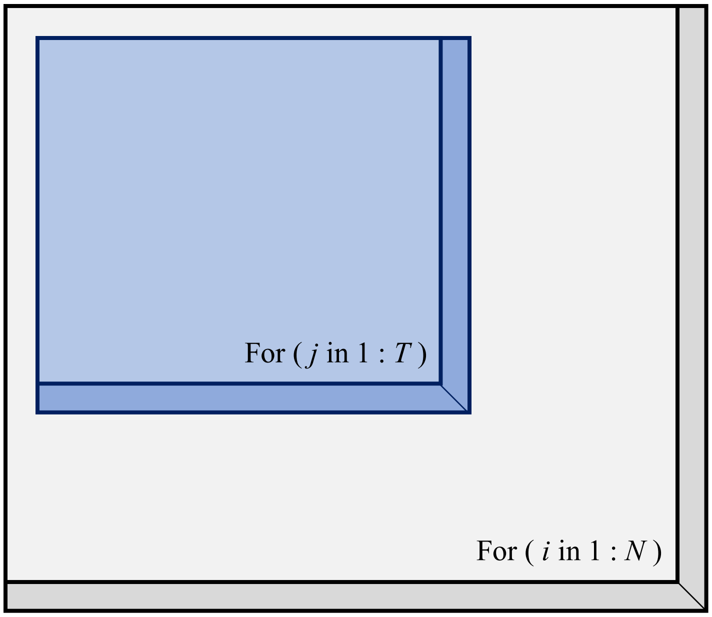


Figure 21h. Graphical depiction of plate structures. Plates represent a repeated feature of a graph, as shown above in an example of two nested plates or sets of indices. The first order plate (or ground plate; grey) represents the range of index i from 1 up to N (i.e., i in 1:N). The second order plate (or top plate; blue) represents the range of index j from 1 up to T (i.e., j in 1:T).

Model Building & Revision

Bayesian hierarchical modeling presents a highly usefully way to derive estimates of statistically modeled unknown parameters and the quantification of uncertainty, which are commonly the focus of inquiry in the ecological sciences and in fisheries analysis (e.g., Cortes, 2002; Jiao et al., 2011). Regarding the latter, development and innovation has been especially robust due to Bayesian methods' ability to bring in data from diverse prior information streams in a robust and significant way for the purpose of performing credible analyses in data-limited situations and to thereby inform decision making (McAllister, Pikitch, Punt, & Hilborn, 1994; Hillborn & Liermann 1998; Punt, Pribac, Walker, Taylor, & Prince, 2000; Punt et al., 2011).

This study recognized the power of such analytical methods and relied heavily on the open access tools that allow for their back-end support in the form of model simulation, and as such has admittedly approached the topic of Bayesian model design in a highly utilitarian and software aided manner. This was accomplished through the delegation of large portions of strictly representational competency and its couched mathematical functionality to the general robustness of publicly available and accessible statistical software suites, specifically WinBUGS/OpenBUGS (Lunn et al., 2000). This afforded the option of circumventing representationally heavy, but perhaps not intrinsically necessary, barriers to entry to Bayesian hierarchical modeling in favor of more general knowledge decision making competencies. This also allowed the capacity to troubleshoot model efficacy through a trial and revision process using, among other things, the native graphical interfaces of such software as a trial-and-error "sandbox" of sorts, at least initially, and in so doing espousing a highly "utilitarian" approach to the general process of model building, based heavily on iterative cycles of model trail, error identification, revision, and subsequent improvement. The improvement and revision pathway in the design of the model was as follows:

1) General theoretical edification of Bayesian Model construction
2) Model trail evaluation
3) Troubleshooting and revisions as necessary
4) Increasingly specified subject matter edification
5) Useful complexity/ feature addition
6) Arrive at new, best-version model
7) Repeat from Step 2

The "evaluate, revise and improve" strategy was carried out over numerous iterations. It is relevant to mention these general details for several reasons. Firstly, greater transparency can be glened by contextualizing the invention process—that is, the model, as it is now presented in its final form, went through various iterations, beyond what would be useful or practical to catalogue formally; though, a roughly organized cache of older, superannuated models is maintined within the authror's extant digital records, should they ever conceivabley require revisiting by a future parties.

Secondly, it is relevant to note that the theoretical knowledge base which informed the model was, for all intents and purposes, aqired and mastered in tandem with the iterative construction of the model and the incorporation of its various improvements, such that the model itself, especially via the navigation of encountered problems over various iterations, acted as a pedagogical device in terms of developing subject matter competencies and greater comfort with operationalizing Baysian concepts and increasingly more advanced mehtods. The simple act of comparing the complexity of the earliest of the authors functional models to the most contemporaneous version demonstrates a clear trajectory of improvement in the form of theoretical understanding and programming fluency. In this way, corrective feedback steps where well integrated into the model's development, resulting in the authors confidence in the current model as presented.

This study conveyed its model through a Directed Acyclic Graph/Model of the Bayesian Hierarchical structure utilized (Figures 23–24). The detailed enumeration of distributions/priors chosen, as well as process functions which generally direct relationships between relevant mathematical components—but may additionally be outputs of interest themselves, as a specific derived relationship between parameters—are defined subsequently within this chapter expressly (Table 10).

These products will demonstrate the conceptual validity of model, rationale for decisions made as to prior and general distribution selection, and should prove immediately relevant as they mimic to a great degree most relevant graphical (thus mathematical and code-based) representations of such models in the leading specialized mathematical software (OpenBUGS, JAGS, Matlab, R, Wolfram, etc.) Succinct and approachable introductions to introductory Bayesian theory as well as highly level analysis and appropriate usage (Lunn et al., 2012) are available in a great many resources and will not be covered in depth in this study more than they already have.

WinBUGS/OpenBUGS Software: MCMC & Gibbs Sampling

Model creation, as well as the majority of affiliated summary statistics, such as marginal posterior means of various unknown target parameters relevant to output, Credible Intervals, and various related graphical assets, were carried out using the WinBUGS/OpenBUGS software and its proprietary coding language (see end of this chapter for copy of code). OpenBUGS is an opensource, free-use software suite developed by the Cambridge University MRC Biostatistics Unit for the purpose of Bayesian analysis of complex statistical models using Markov chain Monte Carlo (MCMC) techniques (Carlin & Chib, 1995; Gilks, Richardson, & Spiegelhalter, 1996; Roberts, 1996). This software is widely used across academic sectors for Bayesian modeling (Web of Science, 2017). Once a hypothetical model has been specified as a full joint distribution over all quantities, whether observables or parameters, sample values of the unknown parameters are taken from conditional (posterior) distribution(s) given those stochastic nodes are populated by observed values.

Although other options are available, the family of MCMC algorithm utilized was Gibbs sampling. Generally speaking, the mathematical purpose of the Gibbs algorithm is to successively draw samples from the conditional distribution of each node given all others in the model (i.e. full conditional distributions; Gilks & Wild, 1992). As Gibbs sampling is a special case of the Metropolis Hastings algorithm, it is appropriate for sampling across difficult full distributions, which, given their complex or atypical structure or status of containing members defined as algebraically non-conjugate to upstream nodes, may be rendered effectively intractable to classical methods of integration not driven by sampling through computer simulation. Under broad conditions, this process eventually produces samples from the joint posterior distribution of the unknown quantities or the marginal distribution of a particular model parameter as specified. The posterior distributions of any Bayesian scheme are concordantly conceptualized as the true value of the distribution of an unknown parameter given prior knowledge—in the form prior probability distributions which may be uninformative numerically speaking beyond distributional behavior, and thus privy to a defined probability space (shape) over an arbitrarily high number of trials (i.e. simulations)—which is updated in the context of the observations and their mathematical likelihood. This diverges from frequentist assumptions of probability theory, in which parameters are deemed fixed and can only be estimated by proxy from trials—that is, in which the values of parameters are not quantified explicitly but rather the confidence values of trials in encompassing mean description of the parameter derived—and in total thus represents the conceptual inverse to Bayesian probability.

Empirical summary statistics (that is, mathematically empirical outcomes derived from multiple novel random simulations of the model provided the basis for computation), can be formed from these samples and used to draw inferences about their true values. Summary statistics of this variety generated by the native analytical capacities of the OpenBUGS software suite, particularly the marginal posterior distributions of a variety of parameters of interest, defined the main analytical output of this research project. These were values of F for 30 species of sharks, biologically based management reference points (F_{msm} , F_{lim} , F_{crash}) as well as Natural Mortality estimates (M) for 17 (of 30) species of sharks, and lastly, numerous other relevant parameters (as well as Credible Intervals for all of the aforementioned parameters), some of which are novel within the extant body of literature.

Derived Observations for $\boldsymbol{F}_{i,j}^{Shk_{LL}^{EEZ}}$

Before the Bayesian model could be run, derived observations (or pseudo-observations) needed to be calculated. Although atypical in construction—as normally collected values for both observed independent and observed dependent variables would be drawn from the real world and extant in advance of external mathematical manipulation—the legitimacy of usage of premodel observations within a Bayesian framework is defined in detail by Raftery et al. (1995) (also de Valpine, 2002) as a special case scenario. That is, the framework remains valid such that a model defined by pre-model information about the outputs (derived variables) consists of observations with measurement error, it may be reduced to standard Bayesian inference, which defines the explicit nature of our case. Expressly, we must first derive mathematically the value of our "observations" which will populate the $\boldsymbol{F}_{i,j}^{Shk_{LL}^{EEZ}}$ node. This body of pre-model values for F, which are manifest by equation rather than measured outright from any natural phenomenon, is derived as the left-hand expression in the Part IV equation of the "Total Assessment Pathway for the Derivation of F" in Figure 22.

Specific Components of Pre-model Calculation of $\boldsymbol{F}_{i,j}^{Shk_{LL}^{EEZ}}$

The same process applies to each species evaluated, so the method for one arbitrary species will be described and should be assumed valid for serialization. For each species of shark evaluated via this model (30 total), species specific inputs were first identified and organized in a tabular format specifically for the purpose of easy bulk and chain calculation. This included values for the Catch Mechanism variables: $q_i^h, q_i^\lambda, PcM_i$.

Values of $q_i^h, q_i^\lambda,$ & PcM_i were included as observed constants when a value could be identified directly in the literature (mainly from Murua et al., 2012) or otherwise derived according to rules for LL risk score designation for Stage 2 ERA as outlined in Daley et al. (2007) & Zhou et al. (2011). The criteria for designation of a specific value as modified for the present study was outlined thoroughly in the proceeding chapter (Chapter II), with specific values included (see Table 9).

Values of $A_{i,j}$ & $A_{i,f}$ were additionally calculated for both Yellowfin Tuna (which remained the same for every species of shark analyzed) and on a per species basis for every shark species analyzed, the process by which these were derived is defined elsewhere (Chapter II).

Values for ρ diverged from the Zhou et al. LL eq. (i.e., Equation 1), in terms of this study's novel, proprietary analytical strategies. Instead of calculating it in a separate system, the value of model term F_i^{YFT} per year (**NB**. F_i^{YFT} per year is the same thing as F_i^T in original Zhou et al. sub-equation ρ**,** just using slightly different notaion; see Equation 3) was calculated in situ as a function of three separate lines of observed data, each parameterized as an observation function containing observation error. The full proof outlining the validity of equivalence between ρ and a functional relationship between these 3 additional variables is defined elsewhere (see section "Pre-Analysis Operations, Part II: Deriving Fishing Mortality Values (F) in Indian Oceanic EEZ for Fishery Dominant Target Species *Thunnus albacares*" in Chapter II); however, the newly integrated data-series included are as follows:

1) $\{F_i^{YFT_{AllGear}^{IOTC}}\}$ i.e., annual, all-gear, YFT fishing mortality (*F*) for the entire IOTC competence area for [2010–'14].

2) $\{C_i^{YFT_{AllGear}^{IOTC}}\}$ i.e., annual, all-gear, YFT catch (*C;* tonnes) for the entire IOTC competence area [2010–'14].

3) $\{C_{i,j}^{YFT_{LL}^{EEZ}}\}$ i.e., annual, long-line only, YFT catch (*C;* tonnes) for only India's Oceanic EEZ for [2010–'14] as reported from three different studies/data-sets. Given that for data-series (j=1 and 2) the last value of both series is in 2011, no data was available for (i=3, 4, 5); ergo, nine values for input into the $F_{i,j}^{Shk_{LL}^{EEZ}}$ observation distribution node are ultimately generated for any arbitrary shark species along with six values of N/A. Nonetheless, borrowing data from its upstream group-level prior means, predictive posterior estimates for indices with no observed values are produced automatically as a feature of hierarchical model constuction, which are used as the basis for updates in successive iterations.

Lastly, we assume that the values of $\{qih, qi\lambda, PcMi\}$ for YFT, which were originally part of the *ρ* sub-equation, are all equal to 1, given that YFT is a target species. Additionally, the value of an Area Constant is included, whose relevancy and stepwise derivation is defined elsewhere (see Chapter II).

With those final considerations in mind, the full final derivation of a pre-model value for any arbitrary shark fishing mortality ($\boldsymbol{F}^{\text{ShK}}$) under this updated framework is outlined in the following graphical section, which links all prior mathematical steps from the pre-model calculations and data acquisition up to the Directed Acyclic Graph. The flowchart, which is conceptually contiguous (and may in essence be viewed as a single graphical entity), is however broken-up into six parts (I–VI) across three figures (Figures 22, 23, & 24), which are described below.

Total Assessment Pathway for the Derivation of F

I. Pre-model calculations & data sources (Figure 22).

II. Unmodified Zhou et al. SAFE longline bycatch mortality equation (Figure 22).

III. Conceptual modifications & notation transition from Zhou et al. equation to derived, present formula for $\boldsymbol{F}^{\text{Shk}}$ in the current study (Figure 22).

IV. Equation for derived, pre-model observations for $\boldsymbol{F}^{\text{Shk}}$ in present study & value streams to be input as data into Bayesian hierarchical model (Figure 22).

V. Pathway options for Catch Mechanism variable selection (parametrization of mean of beta distributions as constant vs. uniform distribution over prescribed risk range) // Beginning of Bayesian hierarchical model parameterization (Figure 23).

VI. Directed acyclic model for remaining body proper of Bayesian hierarchical model for the derivation of F^{Shk} with final enumeration of input pathways for observed data entering the model (Figure 24).

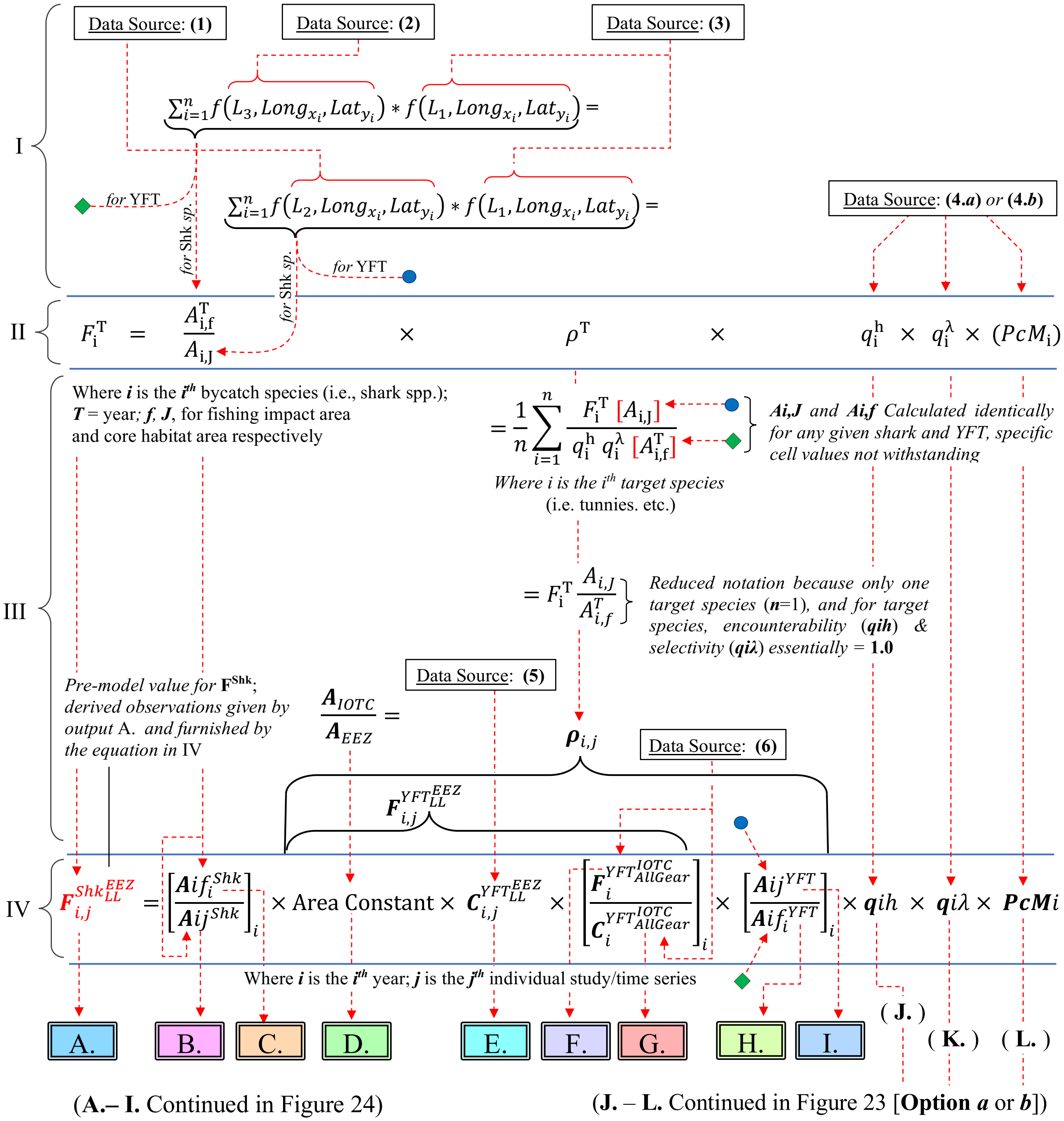


Figure 22. Pre-model calculations, formulaic manipulations & data aggregation / production—Parts I-IV of total assessment flowchart. Data Sources: **(1)**—Component areas of *FJA* to calculate area and grids (custom polygons; marineregions.org). **(2)**—Longline fishing station locations in India's Oceanic EEZ by year: Vijayakumaran & Varghese, 2011[IOTC-2011-SC14]; Vijayakumaran & Varghese, 2012 [IOTC-2012-SC15]; Premchand et al., 2013 [IOTC-2013-SC16-NR09]; Premchand et al., 2014 [IOTC-2014-SC17-NR09]; Premchand et al., 2015 [IOTC-2015-SC18-NR09]. **(3)**—Occurrence probability data (Aquamaps.org / FishBase.org). **(4.*a*)**—Published values from literature (Murua et al., 2012) *or* **(4.*b*)**—Novel Level-2 ERA risk score (point values) (see Chap II, Table 6). **(5)**—Catch (C) data extracted from studies, where j is the jth study: j = 1 is Abdussamad et al. (2012a & 2012b); j = 2 is Hornby et al., (2015a & 2015b); j = 3 is India's National Reports to the Scientific Committee of the IOTC by the Fisheries Survey of India (Various Authors, 2010-2015)]. **(6)**—IOTC YFT stock status literature and reports (Langley, 2015 [IOTC–2015–WPTT17–30]; Langley, 2016). Data on competence area YFT catch and F for YFT for 2010-15.

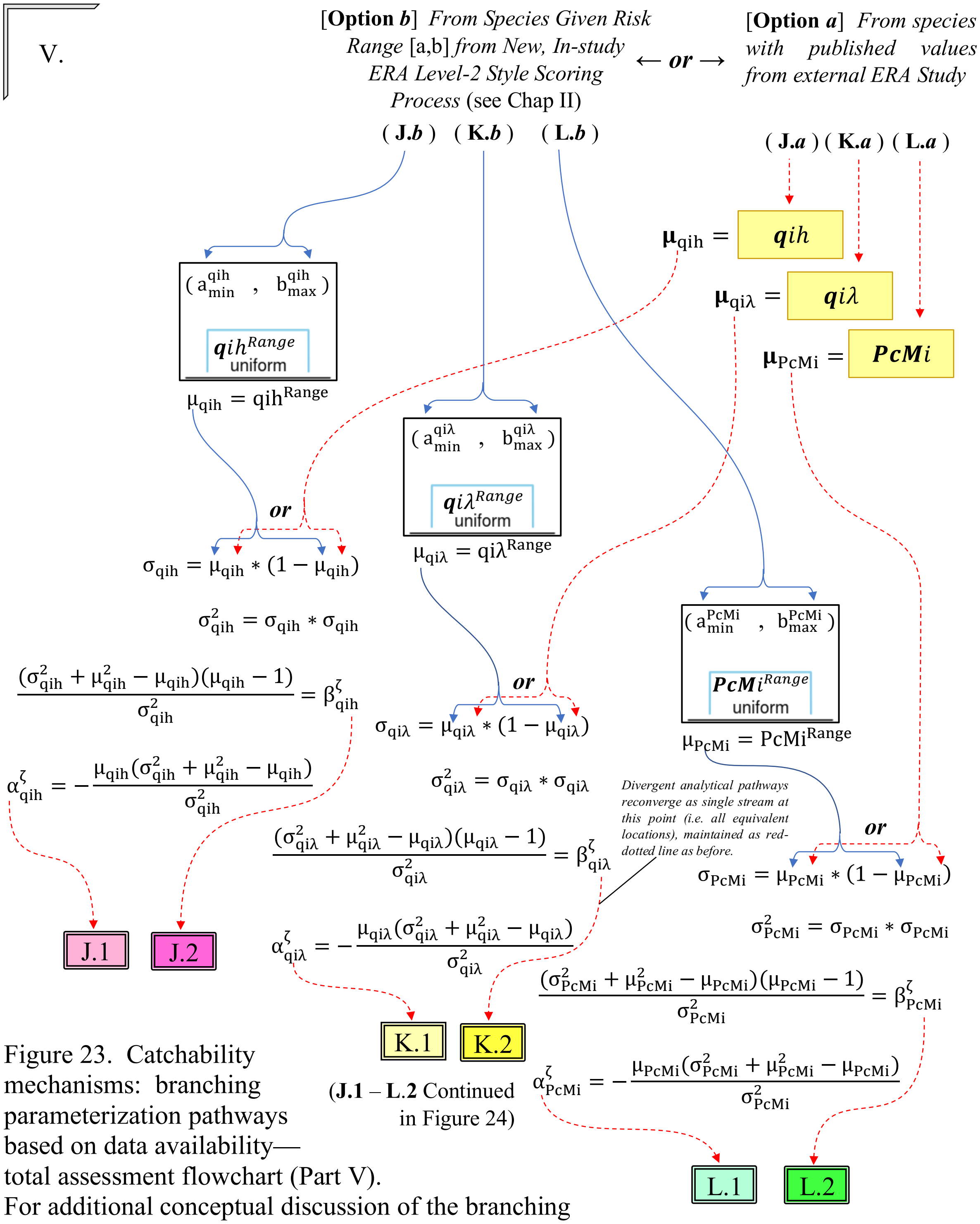


Figure 23. Catchability mechanisms: branching parameterization pathways based on data availability—total assessment flowchart (Part V).

For additional conceptual discussion of the branching parameterization scheme for seeding catch mechanism variables in the models, as well as an explicit, rules-based guide for pursing either of the options respectively in any particular situation, see section "Note on Dual Pathways…". It is important to note that the nodes and/or parameters given here in Figure 23 are part of the formal Bayesian hierarchical model, and would, in a perfect situation, be represented contiguously with the the DAG in Figure 24. Such as it is, they are relegated to a separate page due to spatial limitations.

VI.

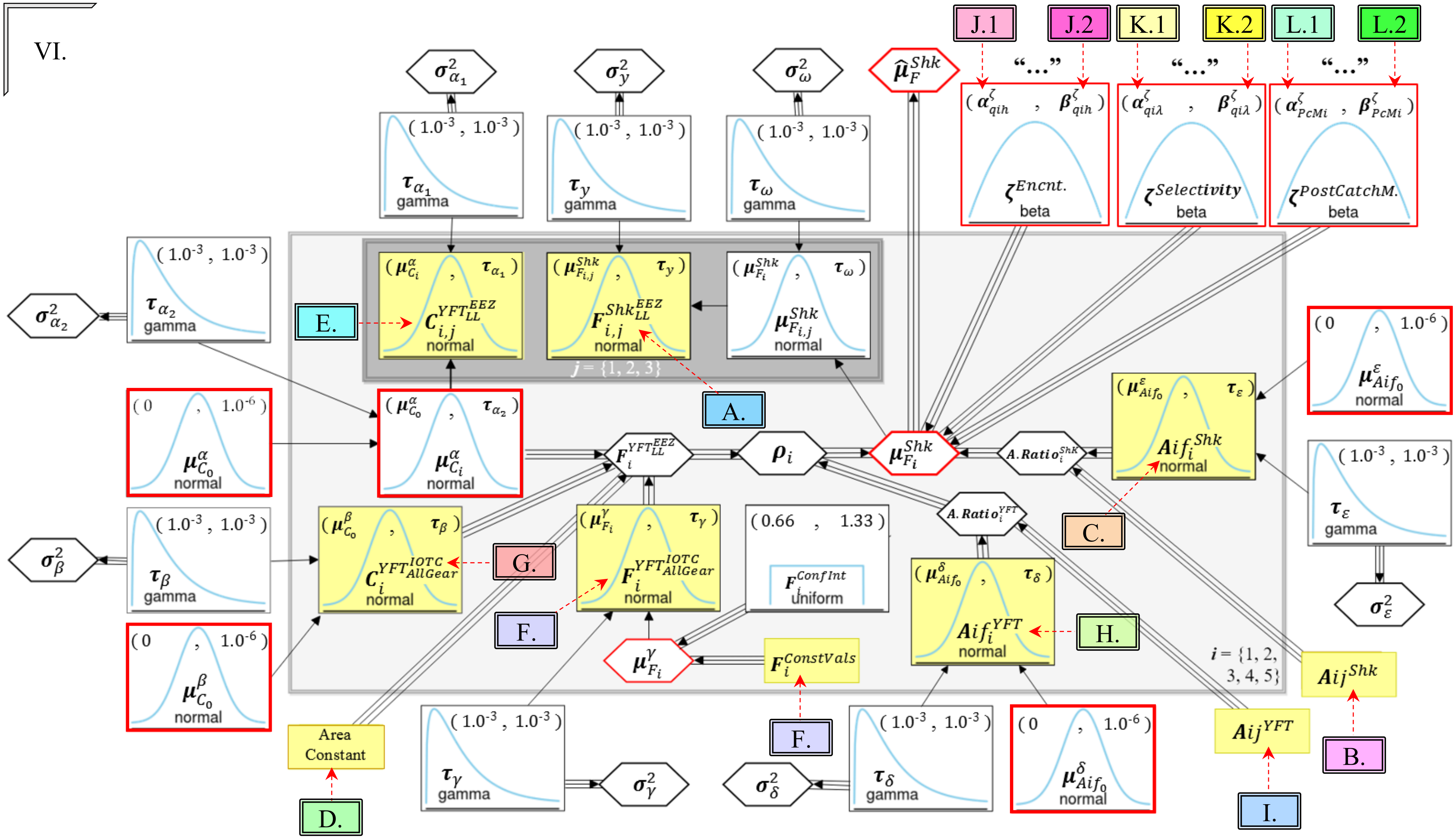


Figure 24. Directed acyclic graph of the Bayesian hierarchical model for the derivation of shark fishing mortality—total assessment flowchart (Part VI). Yellow features (nodes) carry information incorporated into the model as observations or data which are fixed.

These data inputs, denoted by letters (A–L.2), were either derived outright and/or their source identified earlier in the flowchart. Identifiing and preparing these data streams was essentially the entire methodological program in the previous chapter (II), i.e. rendering "pre-model calculations" and organizing "pre-model data aquisitions" for integration into the model. Between the information outlined in the previous chapter and its compact scaffolding within the Total Assessment Flowchart, it should become apparent how every data input (or data stream) is manifest, organized, and then ultimately funneled into the hierarchical model. When stochastic, given the data, these yellow nodes furnish the likelihood functions for relevant submanifolds. Constant nodes operate in the expected fashion. The positions at which data accumulated from prior steps (A.–L.2) are introduced across their likelihood funtions is communicated via dashed arrows (←--------) connecting the Latin letters to specific model parameters, or are simply entered as a static value in the case that the data inhabits a constant node (i.e., yellow squares). The literal values gathered earlier are input at these places, establishing an explicit numerical and conceptual linkage across the analytical pathway from set-up to output. *Note*. Technically, the entirety of the DAG model includes the declaration of Catch mechanism value in Part V; (**"…"**) signifies parts of DAG shown in other pages, which includes the dual potential parameterizations as mentioned previously.

Note on Branching Pathways for Parameterization of Catch Mechanism within Model

In this study, the values of $\{\boldsymbol{q}ih, \boldsymbol{q}i\lambda\ \boldsymbol{PcM}i\}$ are used primarily in two manners: 1) as discrete point-values plugged into the pre-model "observation" calculation of F [shown in the above Part IV equation (Figure 22)] and 2) the parameterization of respective Beta distributions modeling the role of the particular Catch mechanism variable within the Bayesian hierarchical model. Additionally, based upon how the values for $\{\boldsymbol{q}ih, \boldsymbol{q}i\lambda\ \boldsymbol{PcM}i\}$ were furnished—either through 1) the extraction of preexisting published values for the variables directly from the literature (primarily from Murua et al., 2012) or 2) via the process of deriving new values for the variables when none had previously been calculated or published (see Chapter II for process and criteria)—different pathways or designs of the Bayesian hierarchical model were utilized to account mathematically for increased dimensions of uncertainty.

Such as it were, within the Bayesian hierarchical model for the derivation of shark fishing mortality (F) (Figures 23 to 24), the catch mechanism variables are represented as three Beta distributions, one for each variable respectively. Although perfectly valid, a somewhat uncommon mean-wise (μ) parameterization is used for this model's Beta distributions—that is, different from the standard (α, β) parameterization; technically speaking, the mean (μ) may be utilized to compute appropriate values for the (α, β) parameters.

When a value of $\{\boldsymbol{q}ih, \boldsymbol{q}i\lambda\ \boldsymbol{PcM}i\}$ is drawn from the literature, it is entered into the Bayesian model as constant for the corresponding beta distribution's (μ) parameter (see Part V, "Option A") (Figure 23). However, when a catch mechanism variable(s) for a species has not been explicitly measured and/or published in relevant literature, a different process is implmented. In such a case, I was tasked with novel production of both 1) a viable risk-score point-value to be used in the pre-model calculations for F (i.e. “observations of F”), and 2) a feasible min/max bounded estimate of the catch mechanism variable’s uncertainty range. These values, ranging between 0.333–0.999, were drawn from this study’s risk scoring system for otherwise unknown values of catch mechanism variables (see Chapter II for process and criteria). In the case of a species with initially unpublished catch mechanism values, a uniform prior distribution is used to model the beta distribution’s (μ) parameter (which would otherwise simply take a constant value), and the min/max values of the estimated range are entered as the hyperparameters of the uniform prior, (a, b) respectively (see Part V, “Option B”) (Figure 23). The explicit min/max range values used as hyperparameters (a, b) for the uniform priors of $\{\boldsymbol{q}ih, \boldsymbol{q}i\lambda\ \boldsymbol{PcM}i\}$’s Beta distributions respectively are included in Results (Chapter V; see also Table 18(c)).

With these conditions in mind, let us evaluate *Lamiopsis temmincki* (i.e., the Broadfin Shark or Sp. No. 29) where the catch mechanism values have *not* been published. Using the criteria established earlier in Chapter II (Table 6), this species is estimated to express MEDIUM [M] risk for Encounterability, corresponding to a point-value of [.666] for the $\boldsymbol{q}ih$ variable to be used in pre-model calculation of F (Part IV Equation) (Figure 22). Moreover, the total Encounterability risk-range for *Lamiopsis temmincki* has been estimated to span from LOW [L] to MEDIUM-HIGH [M-H] risk, corresponding to values of [.333] and [.8325] to be used as the values of hyperparameters (a, b) in this variable’s respective uniform prior. The rationale for these score designations are outlined in further detail subsequently.

For Encounterability, the Broadfin Shark is a coastal species primarily spending significant time on the sea floor, often in muddy sediments. This is not necessarily a high impact habitat/bathymetric combination for longlining specifically, although the species does appear in longline catches with some regularity (Akhilesh et al., 2016; Akhilesh, Purushottama, Thakurdas, & Kizhakudan, 2017). This latter character, whose score was appraised both in context of significant uncertainty as to its actual, real-world value, as well was with precautionary sensibilities due to its IUCN Endangered Status, was ultimately prescribed the rating of MEDIUM-risk for longline encounterability. The total encounterability risk-range, which takes into account the total plausible value range with respect to perceived uncertainty, was defined as LOW-risk to MEDIUM-HIGH-risk, as the species' nature as a coastal bottom dwelling shark makes it quite unlikely to be optimally HIGH-risk to oceanic longline (most likely effected by trawling, such as it were). Any other risk prescription outside of that (namely L to M-H, via the simple elimination of HIGH-risk form the conceivable range) really cannot be made by the author contingent on the level of information known.

To summarize, the point-value of MEDIUM (i.e., 0.666) is used in the deterministic calculation of derived observation (pre-model values) of F. These F values are then declared as data for the Bayesian model through the specified observation function/node (Figures 23–24). However, as opposed to published cases, in which one may simply input the published catchability mechanism value as constant for the (μ) parameter of the respective Beta distributions, in unpublished cases, a uniform prior distribution [instead of a constant] models the (μ) parameter for the catch mechanism's Beta distribution. The upper and lower limits of the uniform prior (i.e. the min/max values of the estimated risk range, incorporated into the model as the values of hyperparameters [a, b]) are simply the transformed scale values of the risk scores which, in the case of *Lamiopsis temmincki*, were reasoned in the paragraphs above to be defensibly within the possible range of LOW to MEDIUM-HIGH = [0.333, 0.8325].

OpenBUGS Run Details for Section Bayesian Hierarchical Model

Assuming all other values for other observed function nodes have been formatively obtained once, species specific values which must be calculated and loaded into the model before a new, correct model run can be performed include: $\{Aij^{ShK}, Aif_i^{Shk}, F_{i,j}^{Shk_{LL}^{EEZ}}, qih, qi\lambda, PcMi\}$. Once this has been completed, all pre-run mathematical steps have been rendered, and a run can be initialized. For each of the 30 species run through the following model (Figures 23–24), OpenBUGS was used to preform 0.5 million simulations (5.0×10^5) across 3 independent chains.

A “burn-in” (discard) of the first 50,000 iterations (5.0×10^4) was performed on each run; this was done to limit bias accrued at low number iterations. During the initial iterations of a run, the Gibbs sampler is more likely to explore the tail regions of the parameter space thereby incorporating more extreme values into summary values. Since the Gibbs sampler is a learning algorithm, it becomes less likely to do so as more iterations elapse and sampling near the mean becomes more reinforced. Setting aside a set portion of the simulations for burn-in is common practice; there are equations that calculate minimum necessary burn-in intervals, but when a very large number of iterations are conducted any nominally high number will suffice for the burn-in allotment. In this case a burn-in of 50,000 iterations was deemed sufficient.

After 50,000 iterations the model was paused and the model deviance and general suite of goodness of fit statistics (DIC and others) was initialized as a feature of the WinBUGS analytical offerings. For an explanation of DIC and other goodness of fit calculations herein derived, see Spiegelhalter, Best, Carlin, & van der Linde (2002).

Model convergence was obtained ubiquitously over all observed runs of the most recent model, usually well in advance of 50,000 iterations and by extension 0.5million iterations. Once the run was completed, summary statistics in the form of value tables were produced featuring key posterior means of interest which have been included in a variety of focal tables (see Chapter V, Results) as well as essentially all graphical resources which pertain to posterior distributions of focal parameter vis-à-vis boxplots with bars representing Credible Intervals and density strips (see Chapter V, Ancillary Appendix 2, and Ancillary Appendix 3).

Regarding the constituent mathematical components of the Bayesian hierarchical model for the derivation of shark fishing mortality, a table listing all utilized priors, observation distributions, and process functions is given below to add additional contextual detail to the previously showcased graphical representaion (Table 10). Terms and functions given within the table below are equivilent to features by the same name represented within the DAG.

Table 10. Priors, observation distributions, and process functions of the Bayesian hierarchical model for the derivation of shark fishing mortality (F).

Model Equations	Descriptions / Selection Criteria	OpenBUGS Equivalent Code
Observation (Likelihood) Distributions		
$F_{i,j}^{\mathrm{Shk}_{\mathrm{LL}}^{\mathrm{EEZ}}} \sim \mathcal{N}(\mu_{F_{i,j}}^{\omega}, \tau_{y})$	Observation distribution populated by pre-model observations (calculations) of F^{ShK} across all years (i) and studies (j).	`Obs_F_Shark_EEZ[i , j] ~ dnorm(mu_omega[i , j], Tau_omega)`
$C_{i,j}^{\mathrm{YFT}_{\mathrm{LL}}^{\mathrm{EEZ}}} \sim \mathcal{N}(\mu_{C_i}^{\alpha}, \tau_{\alpha_1})$	Observation distribution of YFT catch (C) by LL in tonnes for Indian Oceanic EEZ across all years (i) and studies (j).	`LL_EEZ[i , j] ~ dnorm(annual_mu_YFT_LL_Catch_EEZ[i], Tau_a)`
$C_{i}^{\mathrm{YFT}_{\mathrm{AllGear}}^{\mathrm{IOTC}}} \sim \mathcal{N}(\mu_{C_0}^{\beta}, \tau_{\beta})$	Observation distribution of YFT catch (C) by all gears within IOTC competence area in tones across all years (i).	`C_IOTC[i] ~ dnorm(interannual_mu_YFT_AllGear_Catch_IOTC, Tau_b)`
$F_{i}^{\mathrm{YFT}_{\mathrm{AllGear}}^{\mathrm{IOTC}}} \sim \mathcal{N}(\mu_{F_i}^{\gamma}, \tau_{\gamma})$	Observation distribution of YFT Instantaneous Fishing Mortality Rate (F) by all gears within IOTC Competence Area across all years (i).	`F_IOTC[i] ~ dnorm(annual_mu_F_YFT_IOTC[i], Tau_c)`
$Aif_{i}^{\mathrm{Shk}} \sim \mathcal{N}(\mu_{Aif_0}^{\varepsilon}, \tau_{\varepsilon})$	Observation distribution of Area of LL Fishing Impact for shark species within Indian Oceanic EEZ across all individual years (i). Pre-model calculations of this value are sum of all relevant cells [0.5° Lat × 0.5° Long] area grids subject to a fishing area overlap score of [0-1] on a per-cell basis, which has been weighted by a Species Occurrence probability value of [0-1] on a per-cell basis.	`Shark_Area_Dist[i] ~ dnorm(Shark_Aif, Tau_e)`
$Aif_{i}^{\mathrm{YFT}} \sim \mathcal{N}(\mu_{Aif_0}^{\delta}, \tau_{\delta})$	Observation distribution of Area of LL Fishing Impact for YFT within Indian Oceanic EEZ across all individual years (i). Pre-model calculations of this value are sum of all relevant cells [0.5° Lat × 0.5° Long] area grids subject to a fishing area overlap score of [0-1] on a per-cell basis, which has been weighted an Species Occurrence Probability value of [0-1] on a per-cell basis.	`YFT_Area_Dist[i] ~ dnorm(YFT_Aif, Tau_d)`

Prior Probability Distributions		
$\mu^{\alpha}_{C_i} \sim \mathcal{N}(\mu^{\alpha}_{C_0}, \tau_{\alpha_2})$	This prior distribution represents the expectation of a normal unknown true mean parameter underpinning the differing streams of Catch (C) estimates across the different studies at each year (i). Ergo, estimates by each study for any given gear are similar to a draw from a normal distribution of a common unknown mean, variance based on observation error between years.	`annual_mu_YFT_LL_Catch_EEZ[i] ~ dnorm(interannual_mu_YFT_LL_Catch_EEZ, Tau_a_0)`
$\mu^{Shk}_{F_{i,j}} \sim \mathcal{N}(\mu^{Shk}_{F_i}, \tau_{\omega})$	Prior distribution for the mean (F^{Shk}) estimates for every study for every year. Marginalization with respect to this node after appropriate simulations gives mean posterior estimates even for index coordinates with original pre-model values of NA, due to a study not progressing into said year. This is possible as the posterior is updated with respect to the posterior predicative distribution of NA, treating the unknown value as equivalent to an unknown parameter conditional on both other extant observations and the designated prior distribution, thus allowing for a seamless prediction of unknown values without discounting uncertainty (Barbieri, 2015).	`mu_omega[i , j] ~ dnorm(mu_F_Shark_EEZ[i], Tau_mu)`
$\mu^{\varepsilon}_{\mathrm{Aif}_0} \sim \mathcal{N}(0, 1.0^{-6})$	Prior for mean area of effective fishing impact for Shark spp. over all-years [2010–’14] collectively. The normal distribution represents a standard uninformative distribution of the unknown mean parameter for all years.	`Shark_Aif ~ dnorm(0.0, 1.0E-6)`
$\mu^{\delta}_{\mathrm{Aif}_0} \sim \mathcal{N}(0, 1.0^{-6})$	Prior for mean area of effective fishing impact for YFT over all-years [2010–’14] collectively. A normal distribution represents a standard uninformative distribution of unknown mean parameter.	`YFT_Aif ~ dnorm(0.0, 1.0E-6)`
$\mu^{\beta}_{C_0} \sim \mathcal{N}(0, 1.0^{-6})$	Prior for mean all gear YFT catch within IOTC competence area for all years [2010–’14] collectively. The normal distribution represents a standard uninformative distribution for the unknown mean parameter.	`interannual_mu_YFT_AllGear_Catch_IOTC ~ dnorm(0.0, 1.0E-6)`
$\mu^{\alpha}_{C_0} \sim \mathcal{N}(0, 1.0^{-6})$	Prior for mean for Long Line YFT catch within IOTC competence area for all years [2010–’14] collectively. A normal distribution represents a standard	`interannual_mu_YFT_LL_Catch_EEZ ~ dnorm(0.0, 1.0E-6)`

	uninformative distribution for the unknown mean parameter.	
$F_{\mathrm{i}}^{\mathrm{ConfInt}} \sim \mathcal{U}(0.66, 1.33)$	This uniform distribution roughly mimics the ±80% Confidence Interval of F value as published by Langley (2015), which further bounds prior knowledge in an informative manner.	`F_Conf[i] ~ dunif(0.66, 1.33)`
$\tau_{\alpha_1} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$	Gamma distributions were included as priors for all precision (variance) parameters as they are both maximally uninformative and have expressly positive values (which mirrors real possible observations).	`Tau_a ~ dgamma(0.001, 0.001)`
$\tau_{\alpha_2} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$		`Tau_a_0 ~ dgamma(0.001, 0.001)`
$\tau_{\beta} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$		`Tau_b ~ dgamma(0.001, 0.001)`
$\tau_{\gamma} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$		`Tau_c ~ dgamma(0.001, 0.001)`
$\tau_{\delta} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$		`Tau_d ~ dgamma(0.001, 0.001)`
$\tau_{\varepsilon} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$		`Tau_e ~ dgamma(0.001, 0.001)`
$\tau_{\omega} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$		`Tau_mu ~ dgamma(0.001, 0.001)`
$\tau_{y} \sim \Gamma(1.0^{-3},\ 1.0^{-3})$		`Tau_omega ~ dgamma(0.001, 0.001)`
$\zeta^{\mathrm{Encounterabity}} \sim \mathcal{B}\left(\alpha_{\mathrm{qih}}^{\zeta}, \beta_{\mathrm{qih}}^{\zeta}\right)$	Beta distributions are chosen as they naturally represent a scale parameter with min and max possible parameter values of [0,1]; which are represented in reality via the “catch mechanism” parameters that take on a similar scale value of [0–1].	`zeta1_Encounterability ~ dbeta(alpha_zeta_1, beta_zeta_1)`
$\zeta^{\mathrm{Selectivity}} \sim \mathcal{B}\left(\alpha_{\mathrm{qi}\lambda}^{\zeta}, \beta_{\mathrm{qi}\lambda}^{\zeta}\right)$		`zeta2_Selectivity ~ dbeta(alpha_zeta_2, beta_zeta_2)`
$\zeta^{\mathrm{PostCatchMort}} \sim \mathcal{B}\left(\alpha_{\mathrm{PcM}}^{\zeta}, \beta_{\mathrm{PcM}}^{\zeta}\right)$		`zeta3_PostCatchMort ~ dbeta(alpha_zeta_3, beta_zeta_3)`

	Process functions	
$F_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{LL}}^{\mathrm{EEZ}}} = \text{Area Constant} \times \mu_{C_{\mathrm{i}}}^{\alpha} \times \frac{F_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{AllGear}}^{\mathrm{IOTC}}}}{C_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{AllGear}}^{\mathrm{IOTC}}}}$	Converts mortality rate of YFT for IOTC competence area proportionally to the couched areal, subdivision of the Indian Oceanic EEZ. The value of (F^{YTF}) for a larger area, such as the IOTC competence area, scales directly proportionally with regards to the Ratio of total Catch (C) to area (A) within any sub-delineation. Therefore, value for the total stock (F^{YTF}) with respect to the total IOTC area as cited in the organization's most recent grand Stock Synthesis (Langley, 2015 & 2016) can be scaled directly to any areal subdivision therein, that is, any area in which both sub-delineation specific values of Catch (C) and Area can be adequately estimated for the same time period as the larger parent area. Further restriction as to gear usage component of catch in subdivision can further scale (F^{YTF}) to the resolution of gear-based mortality even when the larger area (F^{YTF}) was initially cited irrespective of gear contribution. This is done by scaling against a necessarily smaller single stream catch in the subdivision area.	`F_EEZ[i] <- Area_Constant * annual_mu_YFT_LL_Catch_EEZ[i] * F_IOTC[i] / C_IOTC[i]`
$\mathrm{A.Ratio}_{\mathrm{i}}^{\mathrm{ShK}} = \left[\frac{Aif_{\mathrm{i}}^{\mathrm{ShK}}}{Aij^{\mathrm{ShK}}}\right]_{\mathrm{i}}$ $\mathrm{A.Ratio}_{\mathrm{i}}^{\mathrm{YFT}} = \left[\frac{Aij^{\mathrm{YFT}}}{Aif_{\mathrm{i}}^{\mathrm{YFT}}}\right]_{\mathrm{i}}$	Note—the numerator and denominator are reversed for equivalent ratio between Shk and YFT; this is not an oversight and consistent with mathematical pretext in "Zhou et al. LL eq."	`S.Aif_Aij[i] <- Shark_Area_Dist[i] / Shark_Aij` `Y.Aij_Aif[i] <- YFT_Aij / YFT_Area_Dist[i]`
$\mu_{F_{\mathrm{i}}}^{\gamma} = F_{\mathrm{i}}^{\mathrm{ConstVals}} \times F_{\mathrm{i}}^{\mathrm{ConfInt}}$	Informative prior value of mean YFT fishing mortality rate is given by situating the prior mean around known values of F. These known values act as the central point for a uniform distribution that is roughly mimetic of the spread of values evinced by the designation of an 80% Confidence Interval on the known mean values (IOTC Stock Synthesis [Langley, 2015, 2016]). This effectively mimics the scope of the unknown parameter for the mean but in a more informative way dependent on robust prior information and initiates a possible parameters space which prevents the drawing of unreal negative values of F mortality. This may not have been possible with a straight forward normal prior of the mean, since	`annual_mu_F_YFT_IOTC[i] <- F_Conf[i] * F_IOTC_2[i]`

	the tail values would likely accrue some negative simulations.	
$\rho_{\mathrm{i}} = F_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{LL}}^{\mathrm{EEZ}}} \times \mathrm{A.Ratio}_{\mathrm{i}}^{\mathrm{YFT}}$	Homologue for ρ values as outlined in Zhou et al LL eq. Simplified, with terms that would be equal to 1 in the case of target species (such as YFT qih, qiλ, PcMi), are absent since they may simply be factored out.	`p[i] <- Y.Aij_Aif[i] * F_EEZ[i]`
$\mu_{\mathrm{qih}} = \mathrm{qih}$	See conditions where alternative uniform priors may be used instead of constant inputs for shape parameters of catch mechanism Beta parameters.	`u1 <- qih`
$\mu_{\mathrm{qi\lambda}} = \mathrm{qi\lambda}$		`u2 <- qilam`
$\mu_{\mathrm{PcMi}} = \mathrm{PcMi}$		`u3 <- PcM`
$\sigma_{\mathrm{qih}} = \mu_{\mathrm{qih}} * (1 - \mu_{\mathrm{qih}})$		`sd1 <- u1 * (1 - u1)`
$\sigma_{\mathrm{qi\lambda}} = \mu_{\mathrm{qi\lambda}} * (1 - \mu_{\mathrm{qi\lambda}})$		`sd2 <- u2 * (1 - u2)`
$\sigma_{\mathrm{PcMi}} = \mu_{\mathrm{PcMi}} * (1 - \mu_{\mathrm{PcMi}})$		`sd3 <- u3 * (1 - u3)`
$\sigma^2_{\mathrm{qih}} = \sigma_{\mathrm{qih}} * \sigma_{\mathrm{qih}}$	All of the process functions grouped herein are involved in the stepwise alternative parameterization of the α and β shape parameters of the “catch mechanism” beta priors in terms of mean and standard deviation point values for beta shape parameters, allowing single published values of catch mechanism means to be input into the model as useful prior information. This is somewhat atypical as the α and β shape parameters are usually not parameterized as such and may instead be given other values, such as Jeffery’s prior [Beta (0.5, 0.5)] which prescribes an uninformative prior probability measure that is otherwise invariant under reparameterization. This would have been the next logical choice if the ERA stage 2 analysis was unable to provide any meaningful min/max values of catch mechanisms risk scores.	`V1 <- pow(sd1, 2)`
$\sigma^2_{\mathrm{qi\lambda}} = \sigma_{\mathrm{qi\lambda}} * \sigma_{\mathrm{qi\lambda}}$		`V2 <- pow(sd2, 2)`
$\sigma^2_{\mathrm{PcMi}} = \sigma_{\mathrm{PcMi}} * \sigma_{\mathrm{PcMi}}$		`V3 <- pow(sd3, 2)`
$\alpha^{\zeta}_{\mathrm{qih}} = -\frac{\mu_{\mathrm{qih}}(\sigma^2_{\mathrm{qih}} + \mu^2_{\mathrm{qih}} - \mu_{\mathrm{qih}})}{\sigma^2_{\mathrm{qih}}}$		`alpha_zeta_1 <- ( -u1) * (V1 + pow(u1, 2) - u1) / V1`
$\alpha^{\zeta}_{\mathrm{qi\lambda}} = -\frac{\mu_{\mathrm{qi\lambda}}(\sigma^2_{\mathrm{qi\lambda}} + \mu^2_{\mathrm{qi\lambda}} - \mu_{\mathrm{qi\lambda}})}{\sigma^2_{\mathrm{qi\lambda}}}$		`alpha_zeta_2 <- ( -u2) * (V2 + pow(u2, 2) - u2) / V2`
$\alpha^{\zeta}_{\mathrm{PcMi}} = -\frac{\mu_{\mathrm{PcMi}}(\sigma^2_{\mathrm{PcMi}} + \mu^2_{\mathrm{PcMi}} - \mu_{\mathrm{PcMi}})}{\sigma^2_{\mathrm{PcMi}}}$		`alpha_zeta_3 <- ( -u3) * (V3 + pow(u3, 2) - u3) / V3`
$\beta^{\zeta}_{\mathrm{qih}} = \frac{(\sigma^2_{\mathrm{qih}} + \mu^2_{\mathrm{qih}} - \mu_{\mathrm{qih}})(\mu_{\mathrm{qih}} - 1)}{\sigma^2_{\mathrm{qih}}}$		`beta_zeta_1 <- (V1 + pow(u1, 2) - u1) * (u1 - 1) / V1`
$\beta^{\zeta}_{\mathrm{qi\lambda}} = \frac{(\sigma^2_{\mathrm{qi\lambda}} + \mu^2_{\mathrm{qi\lambda}} - \mu_{\mathrm{qi\lambda}})(\mu_{\mathrm{qi\lambda}} - 1)}{\sigma^2_{\mathrm{qi\lambda}}}$		`beta_zeta_2 <- (V2 + pow(u2, 2) - u2) * (u2 - 1) / V2`
$\beta^{\zeta}_{\mathrm{PcMi}} = \frac{(\sigma^2_{\mathrm{PcMi}} + \mu^2_{\mathrm{PcMi}} - \mu_{\mathrm{PcMi}})(\mu_{\mathrm{PcMi}} - 1)}{\sigma^2_{\mathrm{PcMi}}}$		`beta_zeta_3 <- (V3 + pow(u3, 2) - u3) * (u3 - 1) / V3`

$\sigma_{\alpha}^{2} = {}^{1}\!/_{\tau_{\alpha}}$	Basic reformulation of Precision values (τ) as Variance (σ^2) for consistency of interpretation, albeit not expressly necessary for model validity.	`Variance_a <- 1 / Tau_a`
$\sigma_{\alpha_0}^{2} = {}^{1}\!/_{\tau_{\alpha_0}}$		`Variance_a_0 <- 1 / Tau_a_0`
$\sigma_{\beta}^{2} = {}^{1}\!/_{\tau_{\beta}}$		`Variance_b <- 1 / Tau_b`
$\sigma_{\gamma}^{2} = {}^{1}\!/_{\tau_{\gamma}}$		`Variance_c <- 1 / Tau_c`
$\sigma_{\delta}^{2} = {}^{1}\!/_{\tau_{\delta}}$		`Variance_d <- 1 / Tau_d`
$\sigma_{\varepsilon}^{2} = {}^{1}\!/_{\tau_{\varepsilon}}$		`Variance_e <- 1 / Tau_e`
$\sigma_{\omega}^{2} = {}^{1}\!/_{\tau_{\omega}}$		`Variance_mu <- 1 / Tau_mu`
$\sigma_{y}^{2} = {}^{1}\!/_{\tau_{y}}$		`Variance_omega <- 1 / Tau_omega`
$\mu_{F_i}^{Shk} = \rho_i \times \mathrm{A.Ratio}_i^{ShK} \times \zeta^{Encnt.} \times \zeta^{Select.} \times \zeta^{PostCatchM.}$	Mean mortality per year (i=1,…5) for F^{Shk}	`mu_F_Shark_EEZ[i] <- S.Aif_Aij[i] * p[i] * zeta1_Encounterability * zeta2_Selectivity * zeta3_PostCatchMort`
$\mu_{F}^{Shk} = \frac{1}{n}\sum_{i=1}^{n}\mu_{F_i}^{Shk};\ \text{where } n = \dim\left(\mu_{F_i}^{Shk}\right);\ \ [\,i = 5]$	Grand mean mortality over all years for F^{Shk}	`interannual_mean_mu_F_Shark_EEZ <- mean(mu_F_Shark_EEZ[])`
Alternative Prior Distributions for q_i^h, q_i^{λ}, PcM_i		
${}_{alt}q_i^h \sim \mathcal{U}(a_{min}^{qih}, b_{max}^{qih})$	When the catch mechanism has no known prior evaluation via a published value, in lieu of a mean point value input as a parameterization for the corresponding catch mechanism Beta distribution, a range of the values, corresponding to the range of plausible risk scores derived (e.g., M to M-H) may be given as a uniform prior to the mean parameterization of the Beta distribution, within the uniform distribution min and max value (i.e. [a, b]) taking the equivalent numerical scale values of the risk score range (e.g., with respect to M to M-H, [0.666-0.8325].	`qih ~ dunif(a_1, b_1)`
${}_{alt}q_i^{\lambda} \sim \mathcal{U}(a_{min}^{qi\lambda}, b_{max}^{qi\lambda})$		`qilam ~ dunif(a_2, b_2)`
${}_{alt}PcMi \sim \mathcal{U}(a_{min}^{PcMi}, b_{max}^{PcMi})$		`PcM ~ dunif(a_3, b_3)`

F = Instantaneous Rate of Fishing Mortality (or simply Fishing Mortality); C = Catch (in metric tonnes); τ = precision; μ = mean; σ = standard distribution; ρ= itself (defined as the primary subcomponent within the Zhou et al LL equation, which corrects for discrepancies between by catch and target); $\mathcal{N}$ = Normal Distribution; $\mathcal{U}$ = Uniform Distribution; Γ = Gamma Distribution; $\mathcal{B}$ =Beta Distribution; qih=selectivity; qiλ = encounterability, as defined by Zhou et al. (2011); PcMi = Post Catch Mortality; YFT = Yellowfin Tuna; Shk=shark by catch species; IOTC = Indian Ocean Tuna Commission; LL=longline gear; Index i = i^{th} year between 2010-14; j = j^{th} study or dataset affiliated with the value or parameter.

Note. OpenBUGS script is included purely for convenience—that is, for component to component parity when analyzing the model codes as well as data declaration table against final representation in full notation (left column). Conventions and actual backend code script rarely changed even in the face of notation revision to avoided propagating errors through iterative and purely cosmetic changes and thus relatively little sense may be drawn from the script text itself as a cogent form of notation beyond basic indices. The conversion key between notations is well proofed so the author implores the reader to fall back on the key even where its seems to break with baseline notational patterns, as there is likely a specific rationale.

NB. The subscripted indices of i and j are not applicable to Aij and Aif (for both sharks and tuna) as well as qih, qiλ, PcMi (note the distinction that none of their i or j representations are subscripted), within the Bayesian model in terms of linkage from subscript to action performed by the model, and remain as purely cosmetic devices to enhance direct interpretation as the conceptual correlate with variables as introduced in preliminary Zhou et al LL eq., as the Bayesian model has as its own unique subscripts which are equivalent but do not have the same notation. It would be obtuse to refer to Aij or Aif outlined previously as something other than itself purely to conform to the notational constraints of the model. This was remedied by not subscripting the i and j terms and just letters in the title of the component.

OpenBUGS Code for Section Bayesian Hierarchical Model

Below is the OpenBUGS code script for the Bayesian hierarchical model for the derivation of shark fishing mortality (F), i.e., the same hierarchical model given by the DAG in Figures 23–24 and whose priors, observation distributions, and process functions are also enumerated in Table 10. Equivalencies between OpenBUGS code nomenclature and specific mathematical expressions can be found as well in Table 10 (i.e., the code given in the rightmost column is equivalent to the mathematical expression in the leftmost column). If entered directly into the OpenBUGS, an exact replica of the model would be produced, although datasets comprising observed data would need to be entered or “declared” manually through a separate step to adequately prime the model to perform a run for a specific species of interest.

```
model{
        for( i in 1 : N ) {
                for( j in 1 : J ) {
                        LL_EEZ[i , j] ~ dnorm(annual_mu_YFT_LL_Catch_EEZ[i], Tau_a)
                        Obs_F_Shark_EEZ[i , j] ~ dnorm(mu_omega[i , j], Tau_omega)
                        mu_omega[i , j] ~ dnorm(mu_F_Shark_EEZ[i], Tau_mu)
                }
                C_IOTC[i] ~ dnorm(interannual_mu_YFT_AllGear_Catch_IOTC, Tau_b)
                F_Conf[i] ~ dunif(0.66, 1.33)
                F_IOTC[i] ~ dnorm(annual_mu_F_YFT_IOTC[i], Tau_c)
                Shark_Area_Dist[i] ~ dnorm(Shark_Aif, Tau_e)
                YFT_Area_Dist[i] ~ dnorm(YFT_Aif, Tau_d)
                annual_mu_YFT_LL_Catch_EEZ[i] ~ dnorm(interannual_mu_YFT_LL_Catch_EEZ, Tau_a_0)
                F_EEZ[i] <- Area_Constant * annual_mu_YFT_LL_Catch_EEZ[i] * F_IOTC[i] / C_IOTC[i]
                S.Aif_Aij[i] <- Shark_Area_Dist[i] / Shark_Aij
                Y.Aij_Aif[i] <- YFT_Aij / YFT_Area_Dist[i]
                annual_mu_F_YFT_IOTC[i] <- F_Conf[i] * F_IOTC_2[i]
                mu_F_Shark_EEZ[i] <- S.Aif_Aij[i] * p[i] * zeta1_Encounterability *
zeta2_Selectivity * zeta3_PostCatchMort
                p[i] <- Y.Aij_Aif[i] * F_EEZ[i]
        }
        Shark_Aif ~ dnorm(0.0, 1.0E-6)
        Tau_a ~ dgamma(0.001, 0.001)
        Tau_a_0 ~ dgamma(0.001, 0.001)
        Tau_b ~ dgamma(0.001, 0.001)
        Tau_c ~ dgamma(0.001, 0.001)
        Tau_d ~ dgamma(0.001, 0.001)
        Tau_e ~ dgamma(0.001, 0.001)
        Tau_mu ~ dgamma(0.001, 0.001)
        Tau_omega ~ dgamma(0.001, 0.001)
        YFT_Aif ~ dnorm(0.0, 1.0E-6)
        interannual_mu_YFT_AllGear_Catch_IOTC ~ dnorm(0.0, 1.0E-6)
        interannual_mu_YFT_LL_Catch_EEZ ~ dnorm(0.0, 1.0E-6)
        zeta1_Encounterability ~ dbeta(alpha_zeta_1, beta_zeta_1)
        zeta2_Selectivity ~ dbeta(alpha_zeta_2, beta_zeta_2)
        zeta3_PostCatchMort ~ dbeta(alpha_zeta_3, beta_zeta_3)
        V1 <- pow(sd1, 2)
        V2 <- pow(sd2, 2)
        V3 <- pow(sd3, 2)
        Variance_a <- 1 / Tau_a
        Variance_a_0 <- 1 / Tau_a_0
        Variance_b <- 1 / Tau_b
        Variance_c <- 1 / Tau_c
        Variance_d <- 1 / Tau_d
        Variance_e <- 1 / Tau_e
        Variance_mu <- 1 / Tau_mu
        Variance_omega <- 1 / Tau_omega
        alpha_zeta_1 <- ( -u1) * (V1 + pow(u1, 2) - u1) / V1
        alpha_zeta_2 <- ( -u2) * (V2 + pow(u2, 2) - u2) / V2
        alpha_zeta_3 <- ( -u3) * (V3 + pow(u3, 2) - u3) / V3
        beta_zeta_1 <- (V1 + pow(u1, 2) - u1) * (u1 - 1) / V1
        beta_zeta_2 <- (V2 + pow(u2, 2) - u2) * (u2 - 1) / V2
        beta_zeta_3 <- (V3 + pow(u3, 2) - u3) * (u3 - 1) / V3
        interannual_mean_mu_F_Shark_EEZ <- mean(mu_F_Shark_EEZ[])
        sd1 <- u1 * (1 - u1)
        sd2 <- u2 * (1 - u2)
        sd3 <- u3 * (1 - u3)
        u1 <- qih
        u2 <- qilam
        u3 <- PcM
}
```

##Note lines of script that are too long for a single line due to spatial constraints on a standard word document page (as seen here) break and continue on the subsequent line at the position of the left most indent, such as line 18 breaking to form line 19; however, when input into a command line, this would simply be a contiguous, single line of code (i.e., line 18 and 19 would simply be a contiguous line 18 in command line). Otherwise, the position of code appears exactly as would be required for direct input and replication in the OpenBUGS program.

Data Declaration for Model Input Values

Table 11 houses the values input into the Bayesian hierarchical model. Values will be referred to by the same names as their respective model placeholder name which is how they are currently identified in the OpenBUGS code for greater convenience when dealing with this dataset, though, refer to the priors table (Table 10) for name-wise equivalence between coding placeholder names and their optimal, presentation notation. There is no difference in any capacity other than the name of the component. Regarding the manner and in what capacity the replacing of each component's data was necessary upon changing the run to a new species, details are provided subsequently.

Values outlined in the subsequent table are equivalent to observed data operating within the model and dispensed back to their prior probabilities' structure through the likelihood values derived via the observation distribution. Alternatively, they may just be constants. Mainly, specific values that populate model components that inform the output values of any species being analyzed, but are not specific to a particular species, are retained for every run as they represent inputs that are common for all possible runs, and influence any of the outputs equally, such as the case with data related to values from the IOTC which are applied at every context equally (i.e., the published values of YFT total catch within the IOTC competence area total [i.e., C_IOTC(i)] would not be changed when a new species of bycatch shark is evaluated, nor would there even be any other from which to choose).

Similarly, once calculated successfully, values relevant to yellow fin tuna are common in their mathematical relationship to every potential bycatch species over every year and can stay in the model fully unperturbed for the entire study. However, values specific to a shark species are exchanged, such as Shark_Area_Dist [i] (the same thing as

Ai,f); similarly, the catch mechanism parameter values (qih, qiλ, and PcMi) and Ai,J values where changed in every new species run. It also goes without saying that to change them, they must first be derived in some capacity, either on an individual basis or alternatively en mass by the author (such as, in the case of the former, the value of Aij, and Aif and for some species their catch mechanism variable values as well). Additionally, values could sometimes just be pulled directly from the literature, as in the case of probably 2/3 of the values of qih, qiλ, and PcMi which were mainly provided by Murua et al. (2012).

Concisely, the entire prior chapter of methods,"Pre-model Operations & Data Acquisition", was overtly related to furnishing many of these values to be input as part of the data declaration. Additionally, for every species, pre-model values of species fishing mortality (F) required computing (see Part IV Equation) (Figure 22) for data declaration as outlined earlier in the chapter. Finally, some values such as tonnes (C) and area values (i.e., Aif, Aij; given in number of grids [0.5° Lat. × 0.5° Long.]) were artificially reduced by a common relevant unit factor to reduce volatility of output (F) values, and in so doing maintain posterior normal distribution within the real range (i.e. F>0) to the extent possible, as negative F is an unreal concept. Thus, catch values (C) were rendered as (1=10^5 tonnes; e.g., 30.1738 vs. 301,738) and area values as (1=10 grids; e.g., 52.226 vs. 522.26). Under normal circumstances this likely would not have been necessary; however, the need to constrain output F to real values given native proximity to 0 prompted this intermediary transition relevant to a lowest common denominator representation of some measurement, unit-based values.

Table 11. Model data declaration: Bayesian hierarchical model for the derivation of shark fishing mortality.

Component	Official Notation	OpenBUGS Equivalent Script	Exchange w/ each species? (Yes/No)[a]	Value[b]	Data Acquisition Process
Structure Defining Values					
Plate Indices	N J	`N` `J`	N	= 5 = 3	N = total years J = total studies
Constant Data					

Catch Mechanism Parameters	q_i^h
	q_i^λ
	PcM_i
		`qih`
		`qilam`
		`PcM`
			Y	= 0.999
				= 0.939
				= 0.974
					See Chapter II sections: "Deriving the Value of q_i^h" ; "Deriving the Value of q_i^λ" ; "Deriving the Value of PcM_i" or "Detailed Component Overview for Central Fisheries Equation"

Area Constant	Area Constant	`Area_Constant`	N	= 27.12606	$\frac{A_{IOTC}}{A_{EEZ}} \approx 27.12606;$ See also Proof I, Chapter II
Const. Values to Center IOTC YFT F uniform Prior	$F_i^{ConstVals}$	`F_IOTC_2`	N	= c(0.1283, 0.1208, 0.1374, 0.1585, 0.1857)	Same as for $F_i^{\mathrm{YFT}^{\mathrm{IOTC}}_{\mathrm{AllGear}}}$
YFT Core Habitat Value	Aij^{YTF}	`YFT_Aij`	N	= 52.22	See Proof II, Part A in Chapter II
Shark Core Habitat Value	Aij^{Shk}	`Shark_Aij`	Y	= 52.98	See Proof II, Part A in Chapter II
Stochastic Data					
YFT Area Effective Fishing Impact	Aif_i^{YFT}	`YFT_Area_Dist`	N	= c(25.683, 24.4905, 20.5512, 13.3725, 9.0775)	Pre-model calcs. of this value are the sum of all relevant cells [0.5 Lat x 0.5 Long] area grids subject to a fishing area overlap score of [0-1] on per-cell basis weighted by a Species Occurrence probability value of [0-1] on a per-cell basis. (See Proof II, Part B in Chapter II).

Shark Area Effective Fishing Impact	$Aif_{\mathrm{i}}^{\mathrm{Shk}}$	`Shark_Area_Dist`	Y	= c(26.117, 24.912, 20.90075, 13.5925, 9.194)	Pre-model calcs. of this value are sum of all relevant cells [0.5 Lat x 0.5 Long] area grids subject to fishing area overlap score of [0-1] on a per-cell basis, weighted by a Species Occurrence Probability value of [0-1] on a per-cell basis. (See Proof II, Part B in Chapter II).
IOTC YFT Catch (all-gear)	$C_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{AllGear}}^{\mathrm{IOTC}}}$	`C_IOTC`	N	= c(30.1738, 32.9305, 40.0501, 40.505, 40.8511)	Lifted from published annual catch values from IOTC for total competence area. (For year-wise catch values, see IOTC, 2016 ["Yellowfin Tuna: Supporting Information]).
IOTC YFT Fishing Mortality (all-gear)	$F_{\mathrm{i}}^{\mathrm{YFT}_{\mathrm{AllGear}}^{\mathrm{IOTC}}}$	`F_IOTC`	N	= c(0.1283, 0.1208, 0.1374, 0.1585, 0.1857)	Transformed from published all-gear annual $(F_t^{YFT}/F_{MSY}^{YFT})$ ratios from IOTC for total competence area. (For year-wise ratios, see: IOTC, 2016 ["Yellowfin Tuna: Supporting Information]; Langley, 2016 [IOTC-2016-WPTT18-27]). where *t* is the t^{th} year from [2010-'14]; $F_{MSY}^{YFT} \ = 0.151;\ F_{Ratio} = F_t^{YFT}/F_{MSY}^{YFT}$ $\therefore\ F_t^{YFT} =\ 0.151 * F_{Ratio}$
EEZ YFT Catch (only-LL)	$C_{\mathrm{i,j}}^{\mathrm{YFT}_{\mathrm{LL}}^{\mathrm{EEZ}}}$	`LL_EEZ`	N	=structure (.Data = c(2.2616, 2.2575, 0.8892, 2.5005, 2.1070, 0.8581, NA, NA, 1.2095, NA, NA, 1.5433, NA, NA, 1.7676), .Dim = c (5,3))	Lifted from published annual LL catch values from various sources, studies are defined along their index designation as such: [Indices: i = 1,...,5 is year 2010,…,2014; j = 1 is Abdussamad et al. (2012a & 2012b); j = 2 is Hornby et al., (2015a & 2015b); j = 3 is India's National Reports to the Scientific Committee of the IOTC by the Fisheries Survey of India (Various Authors, 2010-2015)] [c]
EEZ Shark fishing mortality (only-LL)	$F_{\mathrm{i,j}}^{\mathrm{Shk}_{\mathrm{LL}}^{\mathrm{EEZ}}}$	`Obs_F_Shark_EEZ`	Y	= structure (.Data = c(0.2389, 0.2385, 0.0939, 0.2279, 0.1920, 0.0782, NA, NA, 0.1031, NA, NA, 0.1500, NA, NA, 0.1988), .Dim = c(5,3))	For Pre-model (F) observation generation, also called "pseudo-observations", see the Part IV Equation (in Figure 22) in Chapter III

---

[a] Refers to whether the set of data declaration values for a node, upon running the analysis for a new species, would be exchanged for distinct species-specific values or, alternatively, be retained, as they are values that are permanently necessary for effective

calculation, irrespective of species. The answers are presented as yes or no (Y/N), affirming the need to exchange or negating the need to exchange relative to the specific shark species being analyzed.

[b] For the sake of example, values for *C. longimanus* are provided as stand-ins, though, if a different shark species were being analyzed, values would necessarily need to be exchanged in relavent categories as denoted by (Y) in the proceeding column, explained in note (**a**).

[c] Specific citations for this group of studies combinatively acting as data series [$j = 3$] is thus: (Vijayakumaran & Varghese, 2011[IOTC-2011-SC14]; Vijayakumaran & Varghese, 2012 [IOTC-2012-SC15]; Premchand et al., 2013 [IOTC-2013-SC16-NR09]; Premchand et al., 2014 [IOTC-2014-SC17-NR09]; Premchand et al., 2015 [IOTC-2015-SC18-NR09]).

Chapter IV

Methods, Part III: Bayesian Hierarchical Model for the Derivation of Biological Reference Points (F_{msm}, F_{lim}, F_{crash}) & Natural Mortality (M)

Figure 25. The Shore Temple, Mahabalipuram, by J. Ganz, 1825. Watercolor.

Having described methods for estimating the relevant posterior F values for the shark species being evaluated, thus establishing estimates of fishing mortality by longline effort in this fishery jurisdiction (the oceanic component of India's EEZ), it is now possible to progress to methods for the second, model-based phase of the study—that is, the derivation of biologically based management reference points (F_{msm}, F_{lim}, F_{crash}), as well as Natural Mortality (M), for the same set of shark species.

Fishing mortality (F) as a lone metric is itself only a modest indicator of true status; however, a more exacting management prescription can be derived by framing fishing mortality against species (or class) specific population trends in the form of biological reference points (Mace, 1994).

The second major analytical component of this study used life history (vital) parameters found in the literature or derived through scientifically robust back calculation within the context of population growth relationships to determine management reference points based upon biologically informed population response or tolerance to fishing mortality. By comparing these results to F calculations derived via the previous model in Chapter III in a formal context, status determinations were obtained for individual shark species, fulfilling a major goal of this project.

Vital Parameters Search & Organization

The vital parameter search consisted of detailed reviews of 50~100+ focused academic publications, which either derived novel estimates of Chondrichthyan vital parameters or effectively anthologized past research findings and datasets which facilitated efficient integration into this study. In addition to addressing targeted literature, relevant data points were also obtained frequently from database repositories housing publicly available fisheries and marine species life history information, often populated via direct data dumps from the work of active fisheries scientists and professionals or otherwise drawn from the literature and hosted. Specific aggregator databases and raw-data delivery portals included well known resources such as, but not limited to, FishBase (www.fishbase.org), IUCN Red List (www.iucnredlist.org), Ocean Biogeographic Information System (www.iobis.org), Global Biodiversity Information Facility (www.gbif.org) and Sea Around Us (www.seaaroundus.org). Appropriate scrutiny was applied when utilizing such resources, as they are not always privy to the same degree of error checking as peer-reviewed journal publication, though provide excellent contributions when carefully utilized.

In most cases, individual data points were tracked back to original publications and verified for authenticity and/or modern relevance. All vital parameter data-points utilized in calculations were appropriately organized with reference to full bibliographic attribution, as well as other categorical details, such as study region and sex if specified. The bibliography specific to the collection of vital parameters is substantial, though it is not be fully provided here. For full bibliographic data, contact the author.

Data Availability Conditions for Focal Species

Given the prevalence of encountered "case-by-case" situations and the various modalities employed in combing the literature for viable data points, it was ultimately determined that the application of "general guidelines," as opposed "non-negotiable rules", was the most tractable framework for the incorporation (or alternatively the outright rejection) of viable source material or data points related to focal vital parameters. The goals of the literature review and associated data aggregation was the successful acquisition of at least one credibly derived data estimate for each vital parameter earmarked for the ultimate purpose of producing biological reference points.

Having at least one good value for each of the designated vital parameters would allow for the calculation of a variety of useful life-history/population dynamics driver variables, prerequisite to the ultimate production of the biological-based management reference points of concern $\{F_{msm}, F_{lim}, F_{crash}\}$.

If one value was defined as a desirable core minimum, then certainly, a handful of values for each vital parameter category would be better, so typically, when sufficiently available, the final number of values extracted from the literature was more than one, if for no other reason than at least to function as a second perspective in the final due diligence review of the data accumulated. Effectively, identification of situations of conflicting or otherwise erroneous data character under such circumstances is significantly improved.

As to be expected, some species are much more actively studied than others, and when the case was such, the accumulation of data for these well-scrutinized species remained relatively straightforward, and, somewhat counterintuitively, on occasion required additional procedures for effective organization given the abundance of data. Such well-studied species included the Tiger Shark (*C. cuvier*) for example, with research conducted over many parts of its total global range. For species such as the tiger shark, the author usually would not collect greater than 10-15 published values for a single vital parameter.

In stark contrast to the ‘embarrassment of riches’ found in some species such as the Tiger shark, other species have almost never been scientifically evaluated, apart from formal taxonomic descriptions, or otherwise remain little known outside of localized regimes. This was especially the case with many of the smaller, more coastal South-

Asian endemics. Even with a large cohort of potentially understudied species extant within this study's specific regional catalogue, of the 17 species evaluated in this context, only once did I fail to locate at least one value for all specified vital parameters. This was only the case for one vital parameter for one species, a prior published value of natural mortality (M_{pub}) for the Longfin Mako (*I. paucus*), which upon reflection is admittedly a fairly cryptic and recently described species (Guitart, 1966), so not entirely unanticipated. Expectations for success were exceeded in this capacity; however, the majority of the sharks chosen for the full analysis (and thus requiring an individual vital parameter search), constituted many of the more well-known taxa. Of the 13 species not subjected to the final stage of analysis due to basic time constraints, the extent to which the acquisition of fully populated vital parameter sets would be accomplished with similar ease, subjected to concurrent data profiles (or lack thereof), is unclear, as they remain to be broached in earnest.

Lastly, for those data-moderate species existing comfortably between the two extremes, most of the easily procured references and databases were explored. Although no firm criterion was used to curtail the search effort at any prespecified point, it often naturally plateaued in a similar way after going through the handful of the high-profile studies as well as their bibliographies which would generally yield a useful cross section of parameter estimates. This was generally regarded as a signal of fulfillment of due diligence. However, I frequently had to track down specific and poorly cited data points deep into the older organizational literature and professional reports across various languages to confirm validity of some problematic though highly "cited" data.

Heuristic Strategies & Inclusion Criteria

The initial process for study inclusion was designed in accordance to a preference scheme: preference was based upon geographic and environmental divergence from area of inquiry (oceanic India EEZ / North Indian Ocean)—greater divergence amounting to lower preference. Within the literature review, top desirability was designated for vital parameters derived from stocks of the Indian Ocean or better yet the N. Indian Ocean, Bay of Bengal, Arabian Sea or the Indian EEZ expressly. Closely geographically matched options deemed to be second-best were theoretically given inclusion priority as follows: greater Indian Ocean & Indo-Pacific, Pacific Proper, and Atlantic. Geographic considerations notwithstanding, at the very least I aimed to mainly populate estimated vital parameters means from stocks hailing from similar climatic regimes, especially in the more oceanodromous species.

After adhering to the defined preference criteria for only a short time, I determined that there was, in reality, not really a great enough wealth of material for many species to be so stringently selective in excluding otherwise sound data, only lacking by way of a minor to moderate mismatch in its specific region of analysis. Therefore restriction to Indian Ocean stocks was mostly abandoned, and instead I aggregated whatever data were available for a species of interest, though for the most part avoiding stocks researched in temperate seas (such as Blue Sharks (*P. glauca*) in New Zealand for example), given possible life-history differences between tropical and temperate stocks (Silvestre & Pauly, 1997; White & Sommerville, 2010).

There is noted regional differences in growth patterns and life histories in shark species (White & Sommerville, 2010). The Blacktip shark (*C. limbatus*) as an example, attains a smaller theoretical maximum length and growing faster in the South Atlantic Bight than in the Gulf of Mexico (Carlson, Sulikowski, & Baremore, 2006), whereas substantially larger individuals are caught in South Africa in comparison to individuals from both of these populations (Wintner & Cliff, 1996). However, in data-poor and/or mostly unknown situations, a global aggregate set of shark vital parameters was judged to be a safer starting point, given all considerations, than the values of one study even if they shared some ecological typologies with the theoretical N. Indian Ocean stock.

I was careful not to exclude any legitimate data earmarked for inclusion on arbitrary grounds; only when a data point seemed especially extreme and a valid source study could not be corroborated was it excised. For example, L_{max} values seem to get relayed frequently without substantiation, often including values with no known citation (such as field guides / governmental, internal professional publication). A value was excluded only if it could not be substantiated, which only infrequently occurred.

Calculations of Vital Parameter Point Estimate via Arithmetic Means

Various data points were accumulated for each category of vital parameter (Table 12). An average was then calculated as a simple arithmetic mean of all the values collected. Although the approach for attaining a summary value for the vital parameters was simple in nature, the choice to utilize this method was not arbitrary. For all intents and purposes, we are assuming a state of complete unknown about the life history parameters for Indian Ocean /North Indian Ocean stocks for the great many species and parameters in question; therefore, it would be unnecessary to treat any of the data as more valid than the other—an unknowledgeable observer would not have any criteria as to privilege any information proportionately/disproportionately above or subordinate to any other source—therefore the arithmetic mean serves the purposes of equal priority to all observation hailing from a decidedly unknown state.

Weighting Female Life History Values

The final manipulation of data before the mean value was derived was the prioritization of female life history values as is common in most forms of demographic analysis (Liu, Chin, Chen, & Chang, 2015). Given that, in theory and generally speaking, there are no fundamental limits to male sexual contribution to a population, female reproductive contribution does, on the other hand, indeed have a maximum physiological rate in the form of gestation time, limited ova (in comparison with male sperm which are many times more numerous and cheaply produced comparatively) among other sex specific constraints, and therefore govern the maximum rate of increase for a population as a limiting factor (i.e. 'Bateman's Principle'; [Bateman, 1948]). Additionally, in many shark species there is often the expression of minor to moderate instances of sexual dimorphism, especially in the form of differences the mature sizes between the sexes and initial age of maturity along with other life-history dichotomies (Sims, 2005). It is therefore common for females in many species to achieve a larger maximum size on average, live longer, and ultimately reproduce at a later age. However, these sex-based differences where present are not usually extreme, as far as sexual dimorphism in the animal kingdom goes (Emlen & Oring, 1977), and similarities tend to be common enough to evoke a reasonably accurate, general description of the species irrespective of sex. However, since we are exclusively dealing with aspects of the reproductive character of the species, utilization of general, sex agnostic species parameters may ultimately be detrimental to the total accuracy of affiliated, population relevant calculations. Due to the existence of such commonplace dichotomies in sex-based life history (though definitely not ubiquitous), it is ultimately the female life history that plays the limiting factor in population growth; ergo, including male values would overestimate population growth rates by dampening the apparent time at maturity between generations (Liu et al., 2015). This is not always the case, as general parity across life histories is indeed seen in many species (*C. longimanus* for instance; see [IOTC–2015–SC18–ES18]); however, this is of little mathematical consequence to the scheme presented, as including just the female value, even when sexual parity is expressed, would simply be equivalent to the mixed sex values, and thereby produce no difference in modeling considerations. Concisely, the utilization of female-only parameter values would produce no perceivable mathematical difference even if the species does in reality exhibit sexual parity, and thus a potential externality is eliminated by default.

This study introduces a slight caveat to the general structure of working only with female-based life history parameters, envisioned as a way to incorporate more plausible data without heavily influencing or compromising the principal role of the female as the limiting factor in population growth. The need comes from the reality that many vital parameters have been observed and calculated without reference to sex in the history of modern fisheries science or accumulated in ventures tangential to explicit scientific studies and therefore not recorded with the same level of scrutiny, which would be expected. For example, many L_{max} values are from specimens caught by commercial fisherman, who may not have actively recorded the sex when reporting. Although the practice is more common in the modern literature—that is, to derive values sex-wise for each and any study parameter (e.g. a von Bertalanffy growth coefficient [K] value for stock/population given for males and females respectively) as well as always report organismal sex among other things; this is not necessarily universal, nor has it always been the case. The solution to this problem of what to do with reported parameter values not attributed to any specific sex, both achieving the goal of not eschewing potentially useful data while additionally retaining conceptual integrity of the calculations based on female driven population rate control, is outlined below.

Male (♂) */ female* (♀) */ unsexed* (?) *data-point inclusion rules*. During the data search, in addition to author, region, and value, sex attribution of the parameter was also logged in virtually all cases where it was given expressly. Male data were usually retained in the author's value aggregation database for record keeping purposes; though, all values marked in their respective publications as male originating were not eligible for inclusion in the calculation of the vital parameter summary mean (at least in normal, i.e. sufficient, data-availability situations). Several ad hoc rules were implemented to maintain consistency in deciding potential membership of obtained values within the calculation of the vital parameter summary means:

(1) Values flagged as males, omitted.

(2) Values flagged as female, include twice.

(3a) Unsexed/mixed/combined values, included once.

(3b) If the female and combined values come from the same study, do not include combined value, only female (as it would be, in essence, double counting, though dampened slightly).

(4) If no other viable value can be obtained, then a defined male value can be used (did not encounter this situation for any species evaluated however).

To provide some additional rationale for the adequacy of this scheme, weighting female as a double data (essentially the duplication of a data entry in a series about to be averaged) as opposed to exclusively selecting parameters calculated with regard to female has a handful of benefits. First, there is no need for guesswork regarding sex attribution, as any valid data points are allowed to influence the mean, which updates the knowledge condition from initially totally unknown to a value region of at least credible proximity (even if sexual differences in a vital parameter are extant). However, any confirmed female data points can work to pull the rougher, unsexed value towards the desired female specific expression of the parameter in question, i.e. they may be weighted more heavily via the double counting scheme and thus skew towards the more female-centric version of the value even when some sex attributions are non-existent.

Secondly, an all-female data set that is attributed as such holds the same mean as an all-female data set that is in reality all female but unsexed via reporting omissions, so there are no negative mathematical effects when the sample in reality is furnished by all female values but lack sufficient reporting thereof. So, in effect, weighting the list of values in this manner helps to pull toward the desired female value in the grand scheme but is not self-defeating by being overly strict. It rewards certainty of knowledge of sex at every value that can be confirmed female, while not totally undermining the benefit of at least establishing a rougher, though likely still proximate and credible, estimate furnished with unsexed (and potentially male) or combined values (which may be slightly dampened in relation to true female counterparts), and finally it does not "punish" the final mean calculation when values are in reality female derived but no sex was reported. The only minor drawback is encountered in terms of the change in value when calculating the localized sample standard deviation of the sample of vital parameter values using weighted (double counted) female values. Given a scenario where a set of values are all confirmed female and are calculated under the weighted conditions vs. a scenario where the same set of confirmed female values are unweighted, unlike the calculation of the local mean, which will be identical in both scenarios, the calculation of the local standard deviation will however be different, with the unweighted condition evincing a more expressly correct result. This is simply due to the fact that inclusion of multiple identical numbers will change the value (resulting in less variance), and therefore to a small degree will over express the tightness of values with respect to spread around its central tendency (in a double counted framework). Although we do calculate the sample SD in some upcoming tables, the fact that it is "female weighted" is noted (specifically via the notation σ_{FW}; *FW* standing for female weighted). Moreover, these local, parameter-specific SD values are not used in any down-stream mathematical computations, and thus the value is not propagated into overarching analysis. It is simply furnished as one among several summary calculations to support mathematical description of the cache of values used in the calculation of vital parameter means (see Figures 27d–29d & 31b–33b). Furthermore, the count number of inputs that were identified as female (and thus doubled counted) as opposed to their unidentified (thus single counted counterparts) are included within the vital parameter summary tables for due diligence to aid in back calculation. All factors considered, this minor drawback was deemed tolerable in light of the perceived benefits of the scheme.

Standardization among Total Length (TL), Fork Length (FL), and Pre-Caudal Length (PCL) Length Measurement Typologies

Finally, it is noteworthy to mention that all organism lengths encountered within the literature and utilized for the various length-based vital parameters (L_{max}, L_{mat}, L_{∞}, L_0, etc.) were, when required, transformed to total length (TL) as opposed to the other common measurement tropes of fork length (FL) and pre-caudal length (PCL). Studies that utilized either of those latter two measurement tropes yet otherwise contained values for inclusion in calculations of mean values were converted into TL where possible, or alternatively they were simply omitted if this outcome could not ultimately be accommodated. Conversions were usually facilitated through the proprietary inclusion of an "inter-length conversion" equation provided by authors in their respective publications (See Equations 21 & 22). As there is no consensus as to most accurate measuring length typology, authors often provide transformation equations via multiple type measurements of their own specimens to increase the utility of their results.

An example of this conversion facilitation process is evident in the communication of length data for Spinner Sharks (*C. brevipinna*) measured off South Africa by Allen and Cliff (2000). The authors utilize the mode of precaudal length (PCL) to measure and communicate length data, as opposed to explicitly utilizing the other, similarly common measurement modes of total length (TL) or fork length (FL).

However, in cognizance of the plurality in the literature as to the measurement mode actually utilized by any given study, the authors also derive a conversion key so that data can be directly compared to other measurements/results derived in other publications and vice versa (the specific conversion equations applying only to *C. brevipinna* and not any shark). An example of the conversion formulae given by Allen & Cliff (2000) to convert TL and FL respectively to PCL are the following:

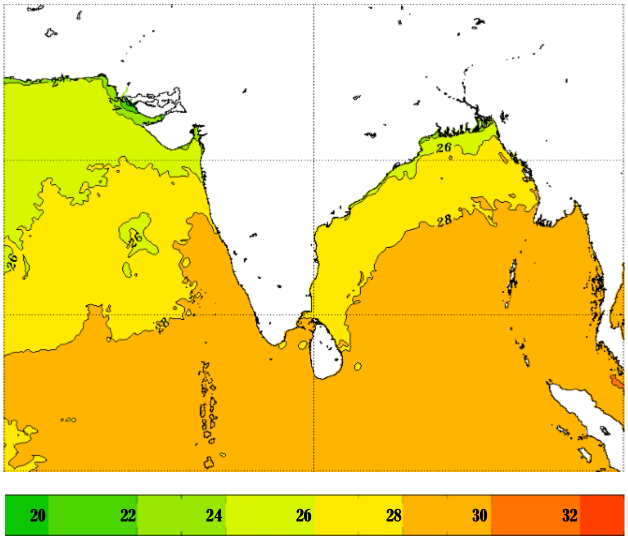
$$PCL = (0.779 \bullet TL) - 9.07 \tag{21}$$
$$[n = 376, r^2 = 0.98]$$

$$PCL = (0.944 \bullet FL) - 3.21 \tag{22}$$
$$[n = 382, r^2 = 0.99]$$

Basic rearrangement of the equations produce equivalent measurements as would be given TL or FL (the former being of relevance to the present study), when measurement in PCL are known and input into the equation and vice versa should the inverse be necessary. Similar conversion equations were also produced fairly commonly across the literature within the discipline (the practice becoming more pervasive in more recent publications), and when relevant they were utilized. This was the case for several species, though, certainly not the majority. As a general comment, this practice proved a highly useful and beneficial scheme for promoting interoperability among studies, and it should be recommended as a best practice for all future publications of this variety.

In addition to data dealing with different components of organism length, the total suite of vital parameters collected within the present study for the purpose of populating downstream Biological Reference Point Equations are given in Table 12.

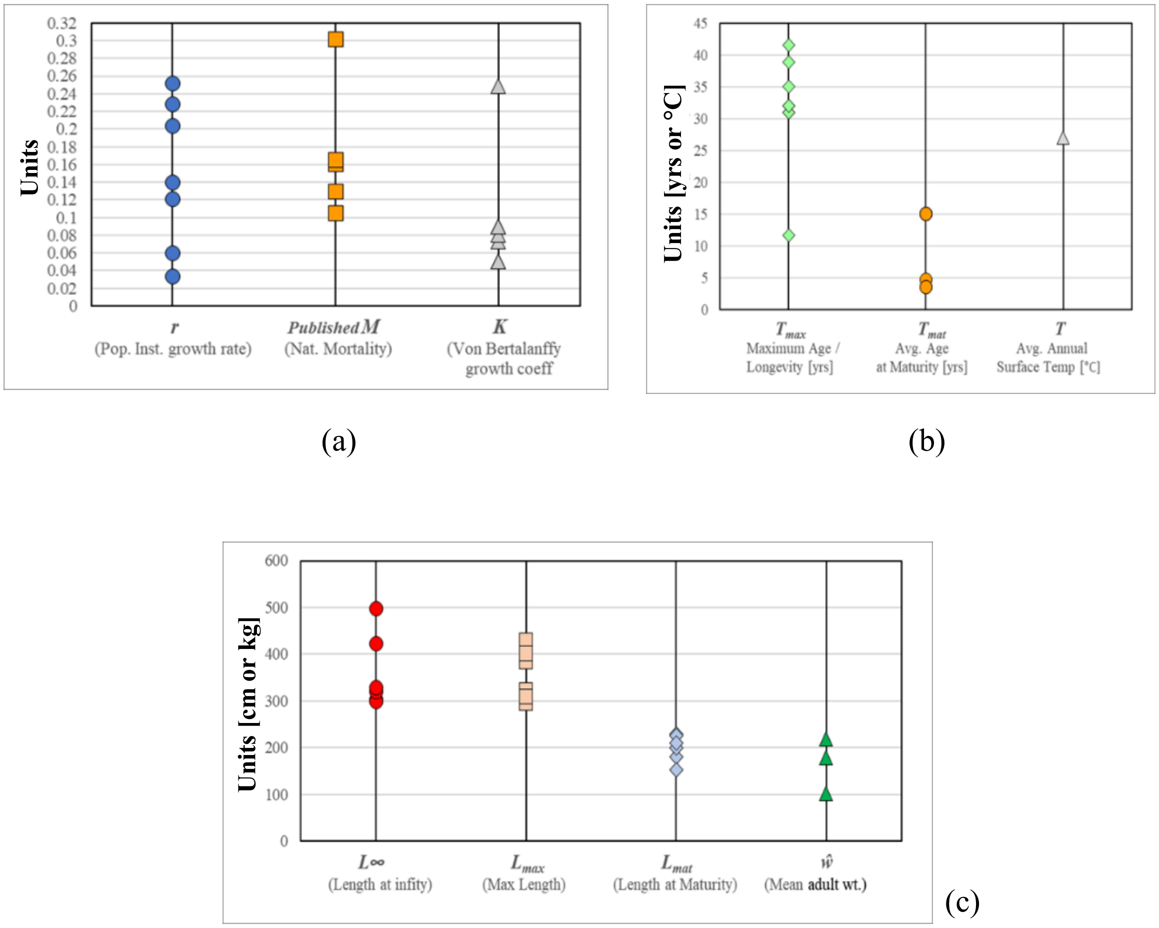
Table 12. List of key collected vital parameters.

Variable	Description	Affiliated Formulas
r	Population Instantaneous Growth Rate	NA
λ	Population Finite Growth Rate	$r = \ln(\lambda)$
ŵ	Mean adult weight; in grams (Blueweiss et al., 1978; Pauly, 1982; Lorenzen,1996)	$\hat{w} = (W_{mat} + W_{max}) / 2$ (Pauly & Murphy, 1982)
M	Natural Mortality (literature published values of M given as M_{pub} to differentiate from values calculated from *M Estimators*)	See section: "Comments on M Estimators"
K	Von Bertalanffy growth coefficient (von Bertalanffy, 1934)	$t_0 = t + (1 / K) [\ln\{L_\infty - L_t / L_\infty\}]$ (Skomal & Natanson, 2003)
L_{max}	Maximum recorded length for a species	See calculation of L_∞ (below)
$L\infty$ (TL)	Length at time infinity (Total Length): Specifically, length of avg. individual given growth to asymptotic length in Von Bertalanffy growth equation (VBGE)	$\log(L\infty) = 0.044 + 0.9841 \log(L_{max})$ Estimating L_∞ from L_{max} (Froese & Binohlan, 2000)
T (°C) Temperature	 Figure 26. Average surface temperature of waters 26-28°C in North Indian Ocean (Blended 5-km SST Analysis) (NOAA, 2018).	

t_{max}	Maximum (observed) age (sometimes denoted Longevity or t_m)	NA
t_{mat}	Average age at maturity (i.e., age at which 50% of the individuals of that age are likely to have reached maturity)	NA
L_{mat}	Length at maturity (same as above but for Length)	NA
L_0 (or L_b)	Size at birth (mm)	NA
t_0	Age at zero length, from von Bertalanffy Growth Equation (VBGE)	NA
ω	Management to Natural Mortality Linkage Coefficient [calculated as 0.43 for elasmobranchs (Zhou et al., 2011) and later as 0.41 (Zhou, Yin, Thorson, Smith, & Fuller, 2012) in its final reprise; the constant value for ω therefore used in this study is 0.41.	NA
$W = a \cdot L^b$	Length-Weight Conversion Curve	Specifically, to derive Lmat and Lmax weight, which is in turn needed to derive "average adult weight"

Vital Parameter Values and Summary Characteristics for Three Species

The total list of vital parameters used in the calculation of summary means from literature sources in both graphical form and in a minor table breaking down general group characteristics per variables for three selected species are shown in Figures 27 [a-d], Figures 28 [a-d] and Figures 29 [a-d]. Similar groups of figures for the additional 14 species may be found in Ancillary Appendix 2. No particular significance was held for choosing these thee species specifically, other than occupying nos. 1, 2 and 3 on the species number key (Table 17, Chapter V). Figures are given here purely for demonstration as they are both contextually and procedurally relevant to this step of the analytical / methodological pathway.



(a)

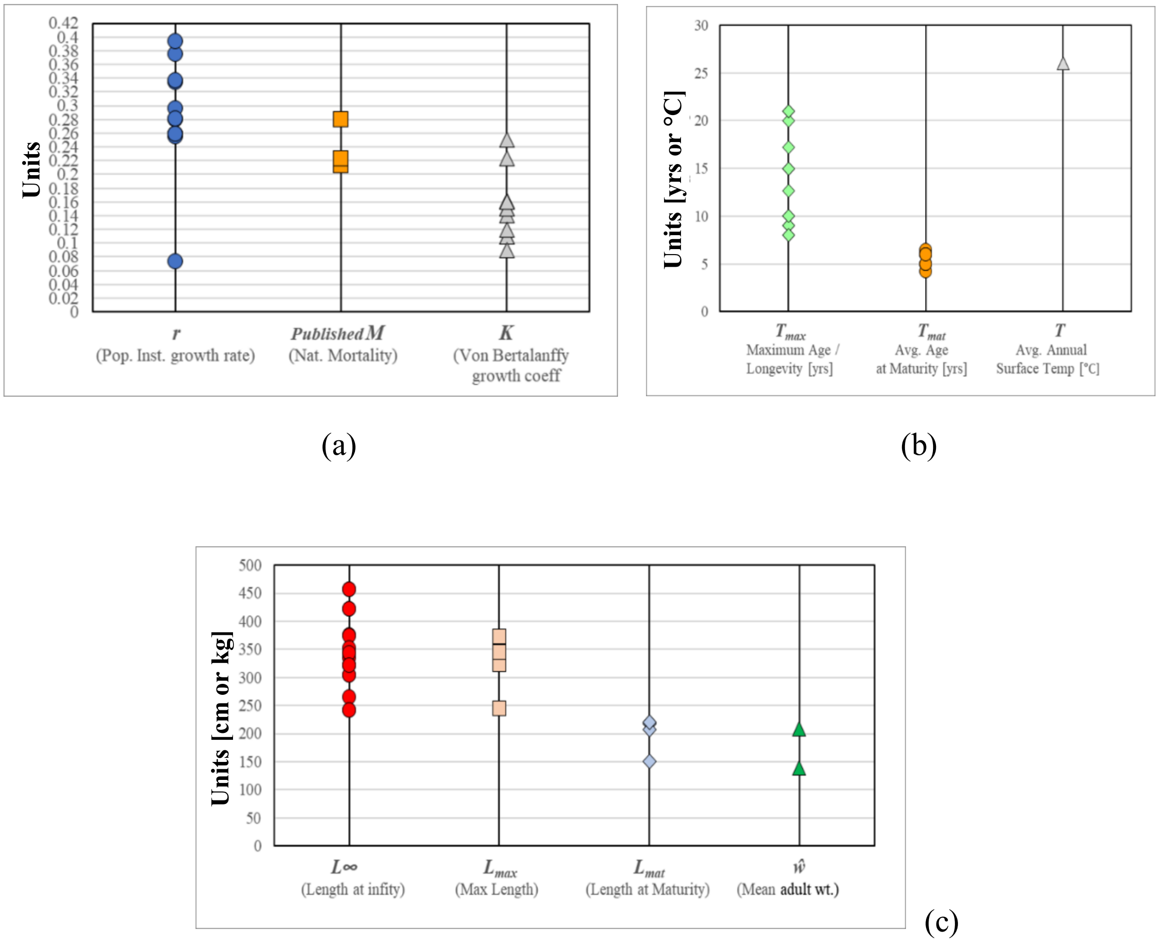
(b)

(c)

	n_{Total}	n_{Female}	μ	σ_{FW}
r	7	0	0.1484	0.0837
M_{pub}	5	0	0.1720	0.0762
K	5	2	0.0974	0.0689
$L\infty$	7	0	352.91	77.32
L_{Max}	7	2	377.22	53.43
L_{mat}	6	6	199.58	27.90
$\bar{w}$	3	0	166.62	58.96
T_{Max}	6	2	31.63	8.98
T_{mat}	6	2	10.84	5.76
T [°C]	1	—	27.00	—

(d)

Figures 27[a–d]. *Sphyrna lewini* (Scalloped Hammerhead): (a–c) Categorical scatter plots of utilized vital parameter values; (d) Preliminary summary characteristics of species' collected vital parameter data.



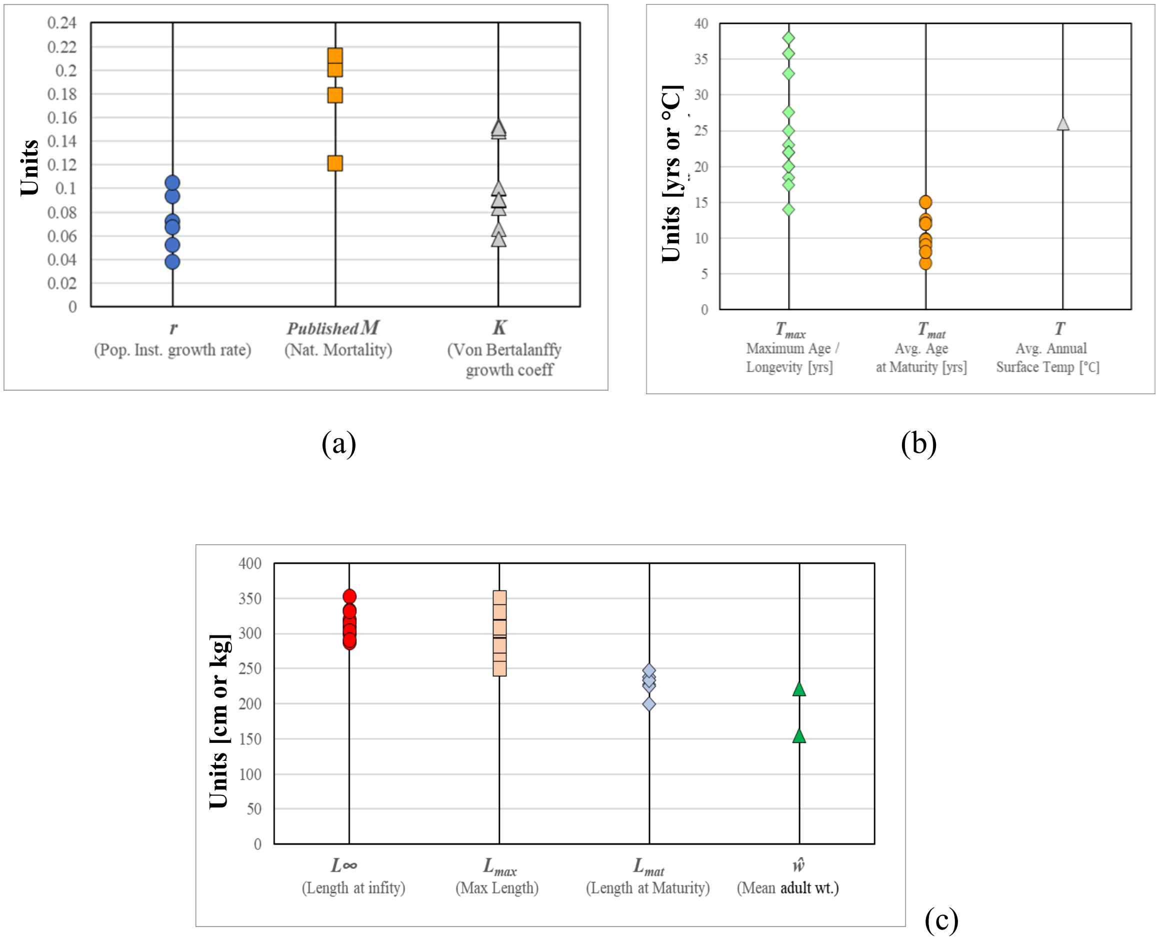
(a) (b)

(c)

	n_{Total}	n_{Female}	μ	σ_{FW}
r	12	0	0.2837	0.0815
M_{pub}	3	0	0.2388	0.0360
K	12	7	0.1534	0.0465
$L\infty$	12	6	345.00	65.18
L_{Max}	4	2	334.14	47.79
L_{mat}	5	5	203.40	28.56
$\bar{w}$	2	0	174.27	49.06
T_{Max}	8	5	13.53	5.00
T_{mat}	8	1	5.52	0.74
T [°C]	1	—	26.00	—

(d)

Figures 28 [a–d]. *Prionace glauca* (Blue Shark): (a–c) Categorical scatter plots of utilized vital parameter values; (d) Preliminary summary characteristics of species' collected vital parameter data.



(a)

(b)

(c)

	n_{Total}	n_{Female}	μ	σ_{FW}
r	6	0	0.0712	0.0249
M_{pub}	4	0	0.1782	0.0404
K	11	4	0.0973	0.0308
$L\infty$	10	0	314.36	20.63
L_{Max}	10	5	295.64	31.75
L_{mat}	6	5	229.00	16.33
$\bar{w}$	2	0	188.28	46.81
T_{Max}	12	5	25.53	7.70
T_{mat}	12	5	10.77	2.67
T [°C]	1	—	26.00	—

(d)

Figures 29 [a–d]. *Carcharhinus falciformis* (Silky Shark): (a–c) Categorical scatter plots of utilized vital parameter values; (d) Preliminary summary characteristics of species' collected vital parameter data.

Estimation of Population Numerical Determinants through Correlated Equations

Significant interest has been expressed consistently and exhaustively regarding the mathematical relationships between aspects of life history in species and important mechanisms or drivers in overarching population dynamics (Blueweiss et al., 1978; Pauly, 1980a, 1980b; Lorenzen, 1996; Cortes, 1998, 2000, 2002, 2016; Zhou, Yin, et al., 2012; etc.). Within the context of data-limited fisheries, the utility of such correlated processes is expressly evident, acting as a method by which key processes can be contextualized and estimated quantitatively without larger scale research studies. As one example, Natural mortality M is rarely evident even with many well studied species and well scrutinized stocks, and far less so for data-scarce situations. Given this general field need, methods to estimate this parameter (as well as many others which may fall into this category) by proxy relationships with phenomena for which data may be more readily available or abundant has been intensively researched. For M specifically, many competing, though conceptually and theoretically unique, relationships have been theorized within the literature and have been subject to ongoing viability assessment, improvements, and general commentary (Kenchington, 2014; Moe, 2015).

Total Mortality, Natural Mortality, and Fishing Mortality

Total Mortality (Z) is a parameter which accounts for the loss of fish in a population through death. In populations experiencing fishing, Z is further bifurcated into two types, based upon agency or primary cause of mortality. The first type is Fishing Mortality (F) which is caused by harvesting, or otherwise inducing anthropogenic sourced organismal death by secondary or tangential means (with mortality vectors ranging from gear abandonment, i.e. ["ghost fishing"], to environmental pollutants and entrained toxicity among others). The second type of mortality is therefore Natural Mortality (M). In addition to natural environmental hazard such as predation and disease, M is caused by the aging and senescence of all living things brought about on different timescales due to foundational biological characteristics, including life history strategies and events (Jørgensen & Holt, 2013), which can then be leveraged as mathematical foci or tether points in the quantification of different time and rate-based aspects of population growth and/or decline on a specific numerical basis.

In the process of monitoring and analyzing populations for the maintenance of sustainable stocks (i.e. stocks that can be fished indefinitely without collapsing) the estimation of M is "one of the most difficult and most critical elements of many fishery stock assessments" and by virtue their understanding and effective management (Hewitt et al., 2007). Significant scientific focus has been lensed at improving the capacity for this estimate both in terms of accuracy and level of empirical input needed (to further support the instances where assessment need and large traditional data profiles are not coexistent, such as the case of the present study; Kenchington, 2014; Moe, 2015).

Mortality estimates are important for fisheries management. The determination of mortality rates is necessary for determining the abundance of fish in a population. By accounting for F in the relationship of total mortality (Z=M+F), remaining death can be attributed to the natural kind or vice versa. Using knowledge of the full scope of death in a population in numerical terms (landing and discards, i.e. F) in addition to the number that would die by natural processes irrespective of fishing, a manager or other interested party may estimate the trend of a population. In essence the mortality rates give one the total deaths of a population; when one compares these to the total births or recruits to the population, it can be determined if a population is increasing or decreasing.

Defining Biologically Based Management Reference Points and their Calculation

In terms of Natural Mortality (M) specifically, Zhou et al. (2009, 2011), Zhou & Fuller (2011), and Zhou, Fuller, & Daily (2012) used this relationship to determine three biologically based management reference points, the calculations of which are especially relevant to data-limited fisheries.

Because population sizes (abundance or biomass) are exceptionally difficult to estimate for dozens of bycatch species, it is expedient to instead focus on the relative quantity—the fishing mortality rate (F)—as the most straightforwardly obtained management reference point. The following three biologically derived management reference points, namely F_{msm}, F_{lim}, F_{crash}, are based on a simple surplus-production model (Figure 30); the full set of three may also be referred to collectively as F_{mgmt}:

- F_{msm} = instantaneous fishing mortality rate which corresponds to the maximum number of fish in the population that can be killed by fishing in the long term. The latter is the maximum sustainable fishing mortality (MSM) at B_{msm} (biomass that supports MSM), similar to target species MSY.
- F_{lim} = instantaneous fishing mortality rate which corresponds to the limit biomass B_{lim}, where B_{lim} is assumed to be half of the biomass that supports a maximum sustainable fishing mortality ($0.5B_{msm}$); and
- F_{crash} = minimum unsustainable instantaneous fishing mortality rate that, in theory, such will lead to population extinction in the long term.

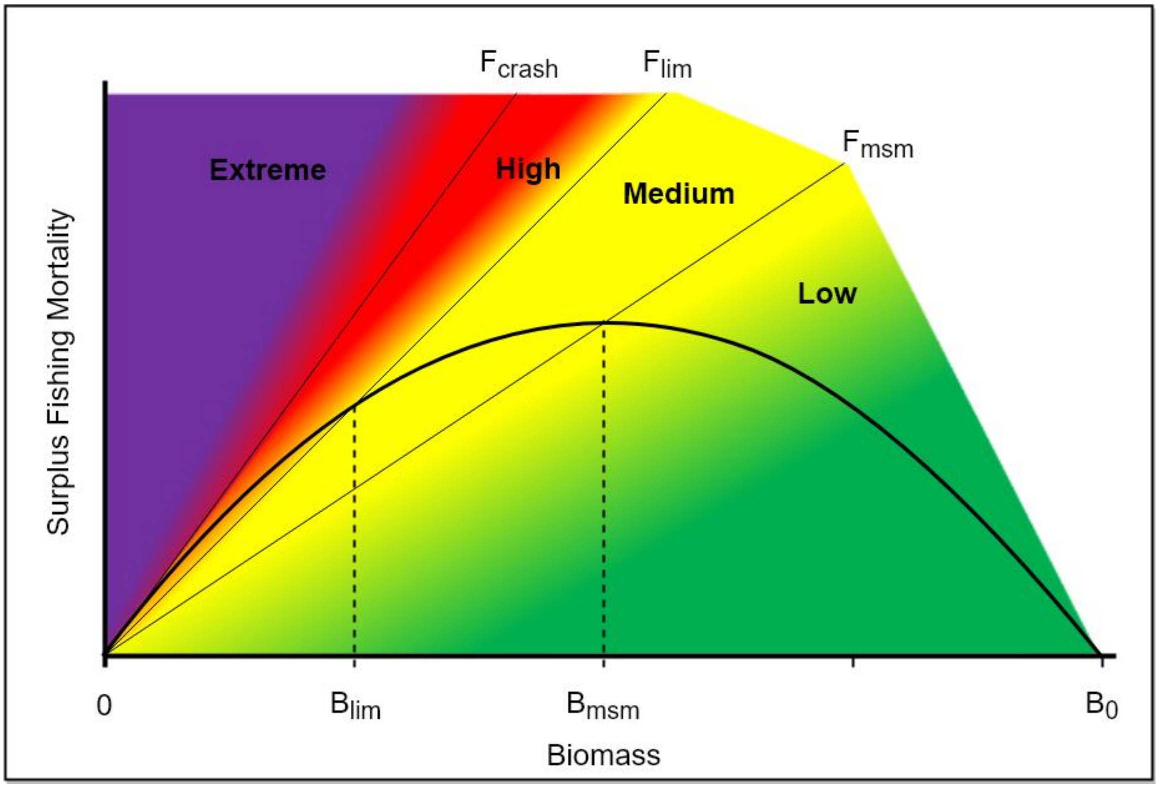


Figure 30. Graphical visualization of stock productivity, biological reference points and ecological risk categories for the management of bycatch species via surplus-production model.

It is assumed that these reference points are a function of basic life history parameters of each species. Specifically, they are linked to the intrinsic population growth rate (*r*) and instantaneous natural mortality (M). Many species have published estimates for *r* and/or M, which can be directly utilized for the calculation of biological reference points; however, when they do not, estimates of M must first be generated. Estimates of M are based on the vital parameters outlined in Table 12. A total of 19 methods are applied to derive these management reference points, which are listed in Table 13.

The calculation of these aforementioned F-based reference points was achieved via first the calculation of natural mortality (M) and/or intrinsic population growth rate (*r*) (Zhou et al., 2011; Zhou, & Fuller, 2011; Zhou, Fuller, & Daley, 2012), which was coupled with a uniquely derived "corrective" constant (**ω**). This constant (**ω**) is expressly defined as 0.43 in Zhou et al. (2011), but revised in a later, more definitive study as 0.41 for elasmobranchs specifically (Zhou, Yin, et al., 2012). I used this most up to date calculation of 0.41 for **ω** (Zhou, Yin, et al., 2012; see also Zhou, Fuller, & Daley, 2012).

In Zhou et al. (2011), Zhou & Fuller (2011), and Zhou, Fuller, and Daley (2012), after calculating F values for species in a similar fashion to this study (aside from the Bayesian hierarchical redesign), the authors then compare the derived F value against the values for F_{msm}, F_{lim}, and F_{crash} which themselves were derived from equations for estimating M and intrinsic population growth rate (*r*). In Zhou et al. (2011), five estimators of M and one estimator of r were used respectively to derive species specific values for F_{mgmt}.

This present study proceeded similarly though in an expanded fashion, namely by using 18 different estimators for M and one estimator of *r* (as opposed to five M and one *r* estimator used respectively by Zhou et al., 2011) with which to glean management reference points F_{msm}, F_{lim}, and F_{crash} in combination with the Zhou, Yin, et al. (2012) ω constant. The 19 derived estimates of F_{mgmt}, the total set obtained via the one estimate of *r* (multiplied by 0.5, 0.75, and 1.0 to obtain F_{msm}, F_{lim}, and F_{crash} respectively) and 18 distinct estimates of M (each produced by one of the 18 outlined M estimators, multiplied by ω, and further multiplied by 1.0, 1.5 and 2.0 to obtain F_{msm}, F_{lim}, and F_{crash} respectively), are defined as pre-model observations (or pseudo-observations) which are incorporated as data into a second Bayesian hierarchical model (Figure 34a) to produce inferences of the mean values of those reference points (or probable ranges via the Credible Intervals).

M Estimators—Analytical Role & Critical Considerations

The aforementioned values of F_{msm}, F_{lim}, F_{crash}, and M essentially function as pre-model observations (or pseudo-observations) which populate the stochastic observation nodes for the downstream calculation of their means via Bayesian methods, functioning much like the pre-model calculation of F described in Chapter III.

As stated earlier, the pre-model estimates of F_{msm}, F_{lim} and F_{crash} were calculated using combinations of the collected life history variable (vital parameter) types listed previously (Table 12) in the context of the M estimator functions (Table 13), which were ultimately multiplied by the "corrective" constant (**ω**) (as well as the values of 1.0, 1.5, and 2.0 respectively) to furnish values of F_{msm}, F_{lim} and F_{crash}, one set of values produced from each estimator. These resulting values of F_{msm}, F_{lim} and F_{crash} acted as data in the context of the Bayesian Hierarchical model. The vital parameter values utilized for computation were themselves composite values, equal to the arithmetic mean of reported values for the parameter across various relevant publications (where available).

Within this study, a maximum of (19) estimates obtained from (19) methodologically unique and theoretically distinct formulaic derivations of F_{msm}, F_{lim}, and F_{crash} were possible. The number of applied methods was limited by the suite of credible vital parameters available, which was unique for each species (i.e. one estimate produces a value for each of the three management reference points [forthwith referred to as an F_{mgmt} set]).

Only one species analyzed was not privy to all (19) estimations—*I. paucus* (Longfin Mako)—for which credible values for vital parameters were only sufficient for the application of 18 methods.

When data availability was satisfactory, the production of estimates was as follows: (1) F_{mgmt} set estimate was derived directly from the arithmetic mean of published values for *r* (instantaneous population growth rate), which was then multiplied by {0.5, 0.75, 1.00} to derive values of F_{msm}, F_{lim}, and F_{crash}. The remaining (18) F_{mgmt} set estimates were derived from unique estimators of M known as M Estimators (Table 13). Estimates of M are derived via a functional, mathematical relationship of values of other various life-history variables, with coupled/correlated linkages there among based upon observation, population ecological theory, or some hybrid thereof. The values of M produced by the individual M estimators were then transformed into F_{msm}, F_{lim} and F_{crash} by first multiplying the initial value of M by the unique linkage variable $\boldsymbol{\omega}$ (Zhou et al., 2011; Zhou, Yin, et al., 2012) defined as (0.41) for Chondrichthyes. The resultant value ($M\omega$) was further multiplied by {1.0, 1.5, 2.0} to derive values of F_{msm}, F_{lim}, and F_{crash} respectively.

The main utility of M estimators within fisheries analysis is to act as a plausible substitute for M in data-limited situations, where a stock-specific, observationally derived estimated value of natural mortality may be unavailable. Hewitt et al. (2007), refers to the former M estimates as "indirect", where the latter, empirically/traditionally garnered estimates are "direct" (field studies specific to the stock of interest, tagging programs, etc.). Given that the derivation of an empirical value natural mortality for a stock is both time and resource intensive, M estimators are of particular utility with respect bycatch/byproduct/non-target species (such as the cohort of shark taxa within this study) or stocks extant within administrative domains that have not historically been subject to direct scientific observation or fisheries management.

The defensibility of M estimators as a viable, albeit imperfect, surrogate for direct observation of natural mortality is based on the following rationale: In pure theoretical terms, population dynamics and its cohort of related metrics are well described by mathematical models, correlated trends, and deterministic equations, whose modulation and resulting graphical geometry are defined by the formulaic relationship of key-variables and the functions thereof. Although in real-world settings, even though externalities, unknowns, and stochasticity play a large role, robust and essentially ubiquitous mathematical relationships remain operational despite the aforementioned confounding factors and can therefore be used to make scientifically relevant and robust predictions, sometimes with high degrees of accuracy. With that said, the search for defensible and widely applicable estimators of particular vital parameters (in this case M) based upon the mathematical relationship with other more easily garnered vital parameters has long been an active sub-field within fisheries science (and ecology in general), given the discipline specific mandate to circumvent resource, time, and data limitations wherever possible while still furnishing scientifically robust assessments, which act as the foundation of policy strategy and management. Ultimately, the reliability of these indirect M estimators is related to the following conditions: (1) the variability of M among species or stocks with the same life history traits, (2) how well M and the life history traits have been estimated for the species or stocks used to estimate the relationship between M and the life history traits, and (3) how well the life history traits have been estimated for the stock of interest (Hewitt et al., 2007). These factors were taken into consideration in selecting and accommodating the M estimators utilized.

The estimation of M for use in data-limited situations has received much critical attention (with the number of published models certainly in excess of 20-30, albeit some more prevalent than others in the literature, with varying degrees of taxa specificity ergo general applicability; Kenchington, 2014). Although a variety of studies have made claims for deriving estimators which furnish general applicability to marine fishes, and additionally are used quite frequently in the literature with confidence in that claim (i.e., for general applicability, at least for marine teleosts, see Pauly, 1978a, 1978b & 1980a, 1980b; Hoenig, 1982, 1983; etc.), more recently the intellectual reception and willingness to utilize such M estimators is more cautious (Francis, 2012; Kenchington, 2014). Francis (2012) and Kenchington (2014) cite plenty of examples of highly incorrect predictions based upon taxa specific life histories, especially with non-teleost fishes such as chondrichthyes (sharks) (Siegfried & Sansó, 2009; Moe, 2015; Cortés, 2016), which for the most part are defined by longer-lifespans and less fecundity, resulting in M estimates which would be excessive to the reality in the field. In so doing, such models are incorrectly calibrated to accurately reflect the different life-history strategies of sharks, often by not accounting for diminished reproductive potential in relation to lifespan and adult size, thereby erroneously implying a more rapid population growth rate than what is actually expressed and ultimately resulting in a management strategy that may allow a greater fishing mortality than what can be sustainably experienced by the stock. This is not to say that the M estimators (specifically the older and more generally designed examples of Pauly, 1978a, 1978b, 1980a, 1980b; Hoenig, 1982, 1983; etc.) result in this eventuality every time, but it has been cited frequently as a necessary consideration when performing generalized M estimates for sharks specifically. Alternatively, some M estimators frequently underestimate in some situation with a variety of taxa (Kenchington, 2014).

Concisely, no M estimator is perfect, even though in aggregate, across a broad range of species they may indeed evince strong correlation between independent predictors and dependent outputs as hypothesized (in this case the latter being M). Each method no matter how modern or old tends to evince certain situational and taxa dependent strengths and weaknesses, which result in under-or over-estimates based upon what variables or vital parameters are used as correlational links.

Solution for estimating M. A common strategy to compensate for the shortcoming of M estimators with respect to specific taxa is to incorporate a variety of M estimators to produce a more tempered, composite estimate of M, which may reduce the risk of generating a dramatically incorrect output. Severe or improbable overestimates can usually be flagged; however, less obvious errors may be masked due to data limitations or unknown yet idiosyncratic expressions of other vital parameters utilized in the M estimator, and, although it may be expressed in one shark taxa, it may not be expressed in others due sensitivity to changes in input variables. In an effort to effectively hedge the production of dramatically incorrect results using these indirect methods, I acknowledged the concern of potential structural volatility encountered when relying on single or even a few estimators of M in two ways.

Firstly, instead of using one, or even four to five estimators of M as was done in Zhou et al., 2011 (a reference of distinction within my research), my study utilizes 18. The 18 M estimators utilized were winnowed down from a larger pool of estimators, with the few that were removed prior to the codification of the final retained cohort being those that were cited as being mathematically inconsiderate of shark biology, usually as they were designed initially for taxa specific purpose, or otherwise just produced implausibly high M estimates across a number of species in preliminary calibration runs and thus removed.

Secondly, aside from the additional two or three M estimators which produced consistent and theoretically refutable outlier estimates—which were thus removed—systemic uncertainty, naturally arising from the inevitable differences in theoretical applicability of the respective methodologies within a composite estimate of M, was accounted for using a 2nd Bayesian model. By framing the calculation of management reference points as a Bayesian hierarchical analysis, quantification of uncertainty in the values of the unknown parameters of interest was possible, namely the three management reference points. Given that no consistent hierarchy or ordering was seemingly evident regarding the values of specific F_{mgmt} and M estimates (i.e. the values of M did not consistently express an overtly comprehensive order on an interspecies basis when calculated) and because small movements in the value of vital parameter frequently entrained larger movements in the output values of M and F_{mgmt} , the output values could be usefully interpreted as a normally distributed and exchangeable random draws about an unknown true mean of M, F_{msm}, F_{lim}, and F_{crash} respectively. In other words, across species, M estimate 1 was not always higher than M estimate 2 which was not always higher than M estimate 3 and so on; essentially no patterns were readily identified and thus the author determined estimated values as likely exchangeable and agreeably represented by a normally distributed construct of observation uncertainty. It is acknowledged however that this intuition could be greatly improved (or potentially subverted to some degree) by actively calculating coefficients of variation (c.v.s) across all M estimators, and further apply corrections based upon those findings (Francis, 2012); however, this step has been omitted from consideration for the time being. Additionally, covariance likely does exist to a certain extent among a variety of combinations of vital parameters, and application of modern understanding of which could further increase accuracy of estimates of other derived life history traits (Thorson, Munch, Cope, & Gao, 2017). The 18 estimators of M (and one estimate of r; 19 total) which in turn produce a new set of estimates for the management reference point values are in Table 13.

Table 13. Utilized M estimators & other F_{mgmt} reference point estimators.

Ref No.	Name of Estimator	Estimator Formulae & Connectivity to F_{mgmt} Ref. Points
	Estimators of *r*	
[A]	Arithmetic Avg. of Previously Published (*r*)'s [a]	$F_{msm} = r/2$, $F_{lim} = 0.75r$, and $F_{crash} = r$ (Ricker, 1975)
	Estimators of *M*	
[1]	Arithmetic Avg. of Previously Published (M_{pub})'s (various)	$F_{msm} = \omega M$, $F_{lim} = 1.5\omega M$, and $F_{crash} = 2\omega M$
[2]	Pauly's Method (1980)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $\ln(M) = -0.0152 - 0.279 \ln(L\infty) + 0.6543 \ln(k) + 0.4634 \ln(T)$ $M = 0.9849 \bullet L\infty^{-0.279} \bullet K^{0.6543} \bullet \tau^{0.4634}$ (Pauly, 1980a, 1980b; Quinn & Deriso, 1999)
[3]	Cortés' Calibration of Hoenig's Estimator I (a) & (b) [b]	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where A) $\ln(M) = \ln(Z) = 0.941 - 0.873 * \ln(T_{max})$, for $L\infty > 100$ cm (Hoeing's equation, 1983 as modified by Cortez, 1998) B) $\ln(M) = \ln(Z) = 1.460 - 1.010 * \ln(T_{max})$ for $L\infty < 100$ cm (Hoeing's equation, 1983 as modified by Cortez, 1998)
[4]	Froese's Method (et al. 2000)	$F_{msm} = \omega M$, $F_{lim} = 1.5\omega M$, and $F_{crash} = 2\omega M$, where: M = 10^[0.566−0.718*log10 (L∞) + 0.02T] (www.Fishbase.org; Froese, Palomares, & Pauly, 2000)
[5]	Hisano's Method (et al. 2011)	$F_{msm} = \omega M$, $F_{lim} = 1.5\omega M$, and $F_{crash} = 2\omega M$, where $M = 1.65 / (t_{mat} - t_0)$ (Jensen, 1996; Hisano, Connolly, & Robbins, 2011)
[6]	Jensen's 2nd Estimator (1996)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = 1.5 * K$ (Jensen, 1996; in Liu et al, 2015)
[7]	Tanaka's Estimator (1960)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = -\ln(0.01) / Tmax$ (Hoenig, 1983; Campana, Joyce, Marks, & Harley, 2001; in Liu et al., 2015)
[8]	Lorenzen's Estimator (1996)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M_w = 3.00w^{-0.288}$ where *Mw is* Natural Mort. at a specific weight input = ŵ (adult mean wt.) (Lorenzen, 1996; McGurk, 1987; Peterson & Wroblewski, 1984 ; Bluewiess, 1978; Ursin, 1967)

[9]	Frisk's Estimator (et al. 2001)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M \approx 0.436\ K^{0.42}$ (Frisk, Miller, & Fogarty, 2001; see also Quiroz, Wiff, & Caneco, 2010; Kenchington, 2014)
[10]	Then's Estimator (et al. 2014) [c]	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = 4.118\ K^{0.73}\ L\infty^{-0.33}$
[11]	Alverson & Carney's Estimator (1975)	$F_{msm} = \omega M$, $Fl_{im} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = 3K / (e^{0.38 \cdot K \cdot tmax} -1)$
[12]	Roff's Method (1984)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = 3K / (e^{KT} - 1)$
[13]	Chen & Watanabe's Estimator (1989)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $T_{mat} < t$; $M(t) = \{ K / (1 - e^{-K(t - t0)})$ . . . . (1a) $T_{mat} \geq t$; $M(t) = \{ K / a_0 + a_1(t - T_{mat}) + a_2 (t - T_{mat})^2$ . . . . (1b) → $a_0 = 1 - e^{-K (Tmat - t0)}$ . . . . (2a) $a_1 = Ke^{-K (Tmat- t0)}$ . . . .(2b) $a_2 = -1 / 2K^2e^{-K (Tmat - t0)}$ . . . . . (2c) → A point estimate may therefore be derived by averaging across half-year intervals for the species-specific age range (Zoe, 2015): $\hat{M} = \frac{1}{T_{max}} \sum_{i=0.5}^{T_{max}} M(t_i)$ .....(3) ■
[14]	Hewitt & Hoenig's Approach (2005)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = 4.22 / T_{max}$
[15]	Hoenig’s Estimator I w/Addendum (1983)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where 1) $Z = 6.99\ T_{max}^{-1.22}$ for fish [d] 2) $Z = 5.20\ T_{max}^{-1.04}$ for cetaceans (sharks) [e]
[16]	Chen & Yuan's Approach (2006)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $t_\lambda' = (t_0 - \ln(0.05) / K)$……....(1) → $\ln(M) = 1.46 - 1.01 \ln(t_\lambda')$…...(2) ■
[17]	Cubillo's Approach (1999)	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = 4.31\ [t_0 - (\ln(0.05) / K)]^{-1.01}$
[18]	Lester's Method I (2004) [f]	$F_{msm} = \omega M$, $F_{lim} = 1.5\ \omega M$, and $F_{crash} = 2\omega M$, where $M = -\ln (1 - g / 1.18)$

---

[a] Not an M estimator, though *r* may be used to directly garner estimates of F_{mgmt} ref points.

[b] Specific usage constraints for elasmobranches furnished by Cortés (1998) to increase applicability in Chondrichthyes based upon species size; also, in Liu et al. (2015).

[c] Revision of Pauly without temperature variable requirement, see Then, Hoenig, Hall, & Hewitt (2015).

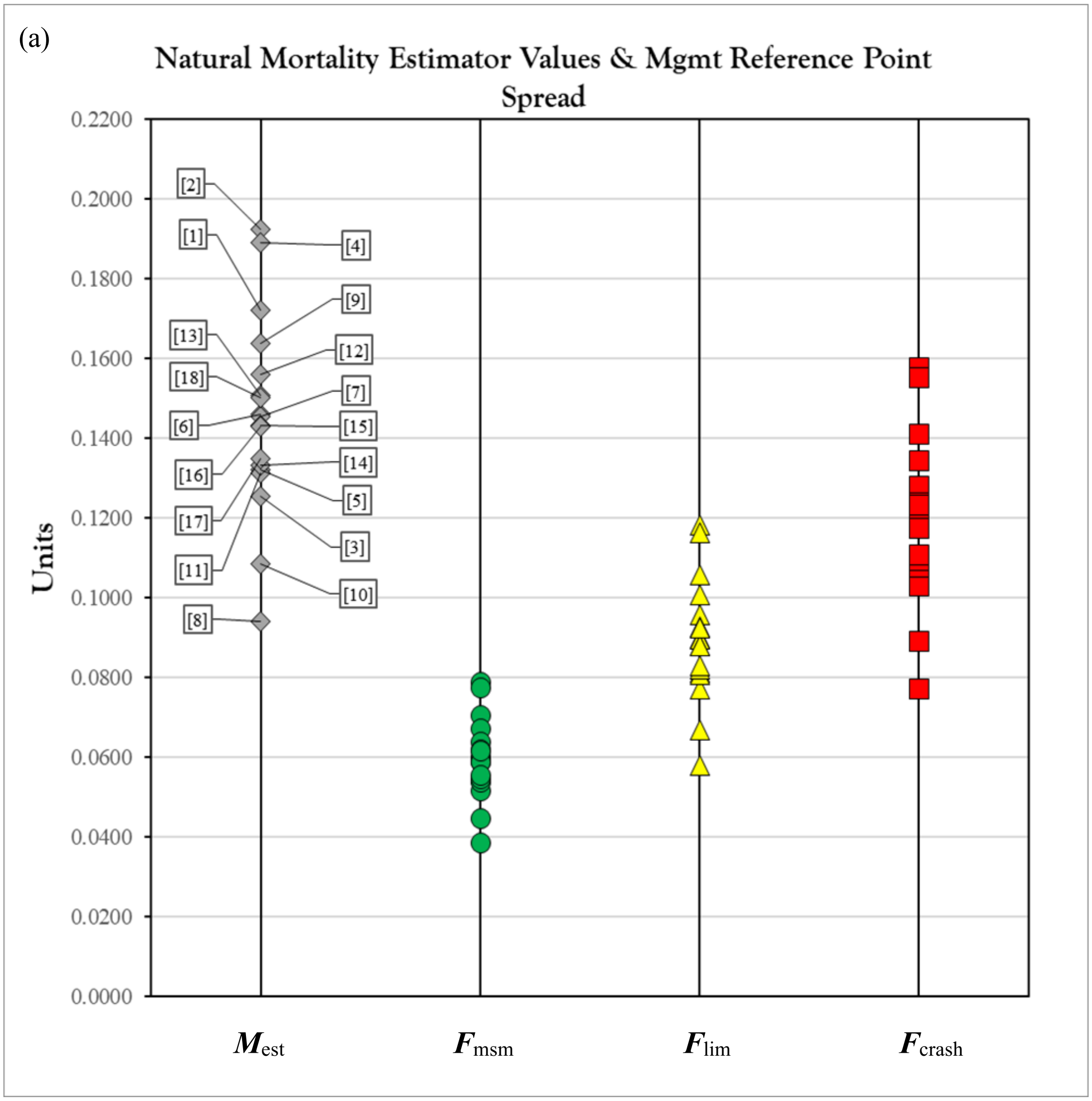
[d] In the context unfished or lightly exploited stocks M may approach Z (Hoenig, 1983; Liu et al., 2015) however the author was reluctant to incorporate many estimators that produced Z values rather than outright M values, this one identified as the only example thereof.

[e] Value (2) utilized for calculation given similar life history traits of larger sharks to marine mammals, rather than teleost fishes.

[f] Variables specific to Lester Growth-Dependent Method (Moe, 2015); c.f. most other estimators utilized, which are largely built around parameters utilized in von Bertalanffy growth model (VBGM).

M Estimator Values and Summary Considerations for Three Species

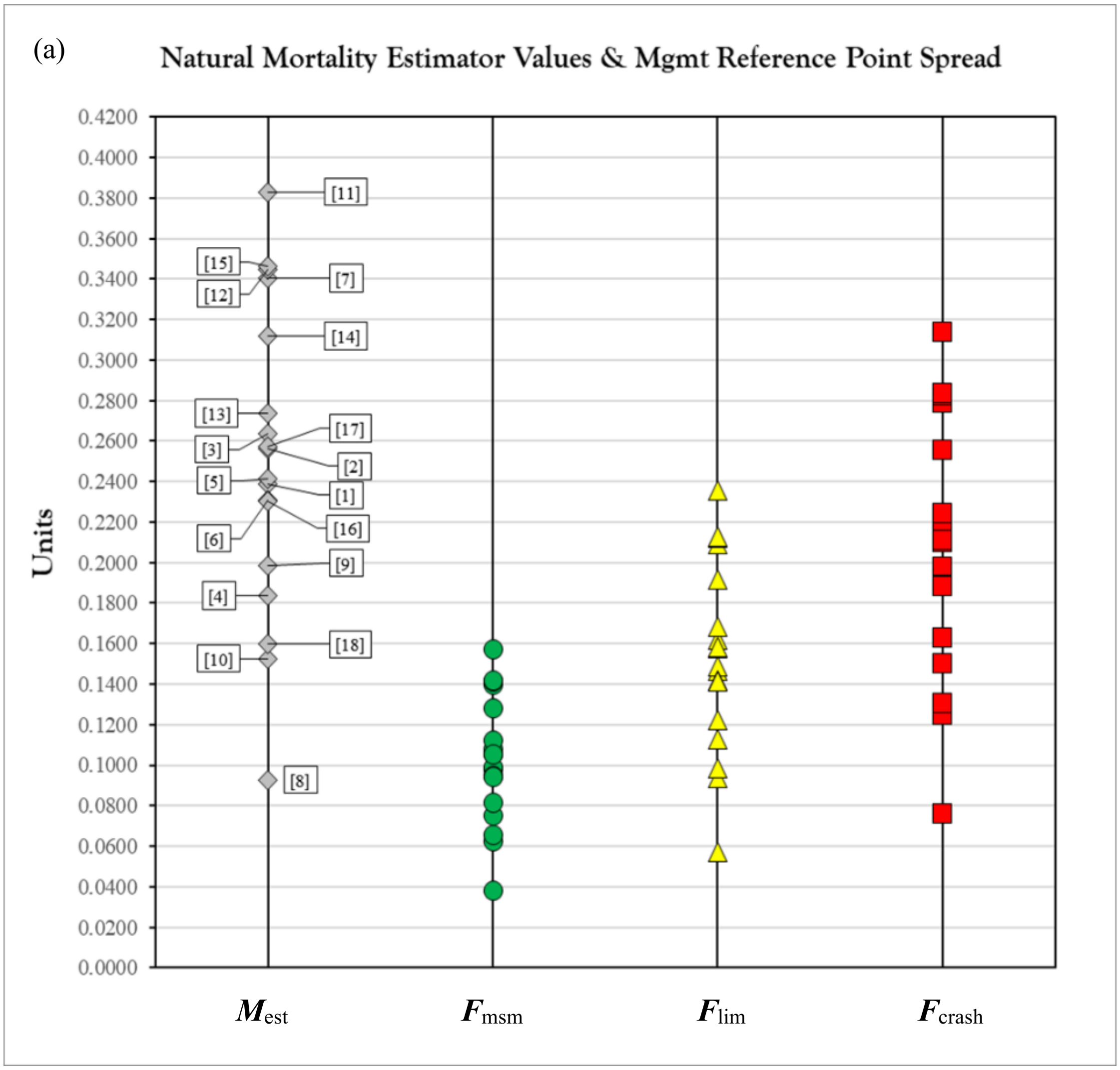
Graphics representing values of M estimators for three species via the outputs of the various estimators are shown in Figures 31 [a, b] – 33 [a, b]. The numerical tags anchored to data points correspond to the M estimator from which they originated (out of a possible 18) are the "Ref No." from Table 13. In this section only three species are represented for the sake of example (*S. lewini, P. glauca, C. falciformis*), the same that were included in Figures 27–29. Corresponding figures for the remaining 14 species were constructed and included in Ancillary Appendix 2.



(b)

	n_{Total}	$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	0.1451	0.0247
F_{msm}	19	0.0603	0.0104
F_{lim}	19	0.0904	0.0156
F_{crash}	19	0.1206	0.0208

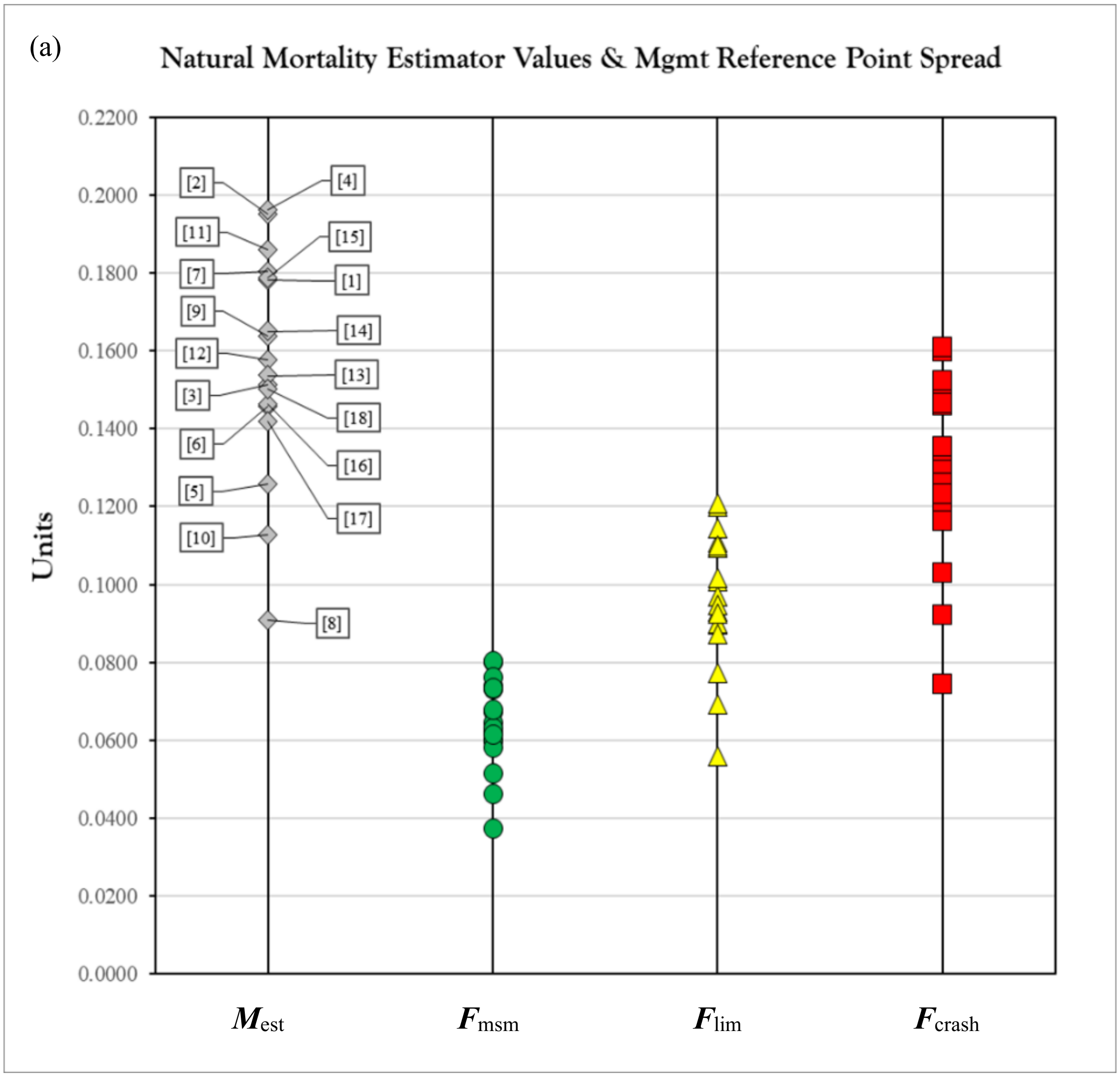
Figure 31 [a-b]. *Sphyrna lewini* (Scalloped Hammerhead): (a) Derived M estimator values & linked reference point spreads; (b) Preliminary summary statistics [maximum likelihood estimates] for species' natural mortality & biological reference points.



(b)

	n_{Total}	$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	0.2504	0.0764
F_{msm}	19	0.1047	0.0317
F_{lim}	19	0.1571	0.0476
F_{crash}	19	0.2094	0.0635

Figure 32 [a-b]. *Prionace glauca* (Blue Shark): (a) Derived M estimator values & linked reference point spreads; (b) Preliminary summary statistics [maximum likelihood estimates] for species' natural mortality & biological reference points.



(b)

	$\boldsymbol{n}_{\text{Total}}$	$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
$\boldsymbol{M}_{est}$	18	0.1567	0.0280
$\boldsymbol{F}_{msm}$	19	0.0627	0.0129
$\boldsymbol{F}_{lim}$	19	0.0941	0.0194
$\boldsymbol{F}_{crash}$	19	0.1255	0.0259

Figure 33 [a-b]. *Carcharhinus falciformis* (Silky Shark): (a) Derived M estimator values & linked reference point spreads; (b) Preliminary summary statistics [maximum likelihood estimates] for species' natural mortality & biological reference points.

Derivation of Biological Reference points via Bayesian Inference

Operating under the assumption of exchangeability (conditional independence), the (19) observations produced via these outlined steps are interpreted as normally distributed random draws/observations of the parameter of interest (i.e., the true mean parameter of F_{msm}, F_{lim}, and F_{crash} respectively). The joint posterior distribution of the unknown parameters of interest, given the data, is proportional to the product of the joint priors and the likelihood function (probability distribution for the data). To zero in on the specific parameters of interest within the total model, the joint posterior distribution (i.e., the probability of all model parameters given the data) is marginalized with respect to the specified parameters of interest (for example F_{msm}, F_{lim}, and F_{crash}), resulting in a marginal posterior distribution, or a posterior distribution for a subset of the model parameters without regard to the other parameters. Because marginalizing involves integration which becomes formally intractable in high dimension, Monte Carlo Markov Chain simulation is performed to derive random observation about the total parameter space of the joint posterior distribution through iterative simulations and coupled learning algorithms, such as a Gibbs Sampler. Observations of the total joint posterior distribution effectively map out the dimensions of the total joint posterior parameter space, and marginalization is accomplished trivially by constructing a distribution based upon sample values contributed only via the specific dimension of interest, dimensions being equivalent to parameters. From the marginal posterior distribution, point estimates of unknown parameters values are computed as the mean (highest point of the marginal posterior distribution), and Credible Interval ($C_{R}I$) estimates can be calculated by computing the end points of an interval that correspond with specified percentiles of the marginal posterior distribution. Via this process, point estimates of unknown model parameters, i.e. true means of F_{msm}, F_{lim}, F_{crash}, are obtained along with the quantification of uncertainty in the values of said parameters in the form of associated Credible Intervals. The DAG showcasing this particular Bayesian network is given in Figure 34a.

Additionally, since so many estimates of M were utilized for the linked estimation of F_{msm}, F_{lim}, and F_{crash}, it provided an opportunity to subject the parameter of M itself to a framework of Bayesian inference through a third self-contained (though relatively simple) hierarchical model, as nearly 20 estimates were produced for each species analyzed simply to furnish pre-model observations for the biological reference points. Thus, this coupled data preparation outcome provided an opportunity to calculate species specific posterior means of M via a 3rd Bayesian hierarchical model due to the convenience of relevant inputs. Using this third hierarchical model (Figure 34b), posterior mean values for Natural Mortality M were obtained additionally for all species included in this second phase of analysis (i.e. subject to derivation of F_{mgmt}). This exercise resulted in what is believed to be some of the first worldwide estimates derived for M for a few species, most notably the Longfin Mako (*I. paucus*).

Bayesian Directed Acyclic Graphs for Calculating Biological Reference Points (F_{msm}, F_{lim}, and F_{crash}) and Natural Mortality (M)

The DAG for the Bayesian hierarchical model for the derivation of biological reference points (F_{msm}, F_{lim}, and F_{crash}) is given in Figure 34a, and the DAG for the Bayesian hierarchical model for the derivation of Natural Mortality is given in Figure 34b. Conventions of DAG construction are identical to those explained in the prior chapter (Chapter III). The run metrics of these two hierarchical models were also identical to that of the previous model for F, executed via the WinBUGS/OpenBUGS software. As before, a total of 500,000 simulation iterations with a burn-in factor of 50,000 iterations was carried out for each model run performed once on 17 of the 30 species for which fishing mortality (F) values were initially derived. Runs were not performed (and thus respective values of biological reference points and Natural Mortality were not obtained) on the remaining 13 species for which initial fishing mortality values were found due to time restrictions in the completion of the study. Regarding the constituent mathematical components of the Bayesian hierarchical model for the derivation of biological reference points (F_{msm}, F_{lim}, and F_{crash}) and the Bayesian hierarchical model for the derivation of Natural Mortality respectively, two a tables listing all utilized priors, observation distributions, and process functions (Tables 14 & 15) are given as well to add additional contextual detail to the showcased DAG graphical representations (Figures 34a & 34b). Terms and functions given within the tables are equivalent to graphical features by the same name represented within their respective DAGs.

It is worthwhile to mention that due to the relative computational and structural simplicity of these two models (at least by comparison to the initial model for the derivation of F in Chapter III), it was possible to compute both models in the same run session. This was done purely for the purposes of study convenience. The models were fully quarantined and not subject to inter-model information sharing of any kind, other than an initial random number seed, effectively acting as two separate models conducted under the convenience of a single run. Ultimately, this scheme cut the time required to perform repetitive, manual data declaration tasks by the user effectively in half, which is non-trivial, but has no further rationale other than pure convenience. Evidence of the simultaneous run of both models is seen in the OpenBUGS code for the section Bayesian Hierarchical model listed below, which represents an exact copy of the code utilize to run the simultaneous analyses. Equivalencies between OpenBUGS code nomenclature and specific mathematical expressions can be found as well in Tables 14 and 15. If entered directly into the OpenBUGS software, an exact replica of the model would be produced, although datasets comprising observed data would need to be manually entered or "declared" through a separate step to adequately prime the model to perform a run for a particular species of interest. An overview of this declaration step and a case example of specific data points utilized for a particular species (*C. longimanus*) is given in Table 16.

```
model{
	for( i in 1 : calculated_mgmt_refpoint_types_A ) {
		for( j in 1 : mgmt_refpoint_est_eqs_A ) {
			mu_A[i , j] ~ dnorm(mu_Fmgmt_A[i], Tau_A)
			y_A[i , j] ~ dnorm(mu_A[i , j], Tau_within_A)
		}
		mu_Fmgmt_A[i] ~ dnorm(theta_A, Tau_btw_A)
	}
	for( n in 1 : M_estimators_B ) {
		mu_NatMort_B[n] ~ dnorm(theta_B, Tau_btw_B)
		y_B[n] ~ dnorm(mu_NatMort_B[n], Tau_within_B)
	}
	Tau_A ~ dgamma(0.001, 0.001)
	Tau_btw_A ~ dgamma(0.001, 0.001)
	Tau_btw_B ~ dgamma(0.001, 0.001)
	Tau_within_A ~ dgamma(0.001, 0.001)
	Tau_within_B ~ dgamma(0.001, 0.001)
	theta_A ~ dnorm(0.0, 1.0E-6)
	theta_B ~ dnorm(0.0, 1.0E-6)
	Variance_A <- 1 / Tau_A
	Variance_btw_A <- 1 / Tau_btw_A
	Variance_btw_B <- 1 / Tau_btw_B
	Variance_within_A <- 1 / Tau_within_A
	Variance_within_B <- 1 / Tau_within_B
}
```

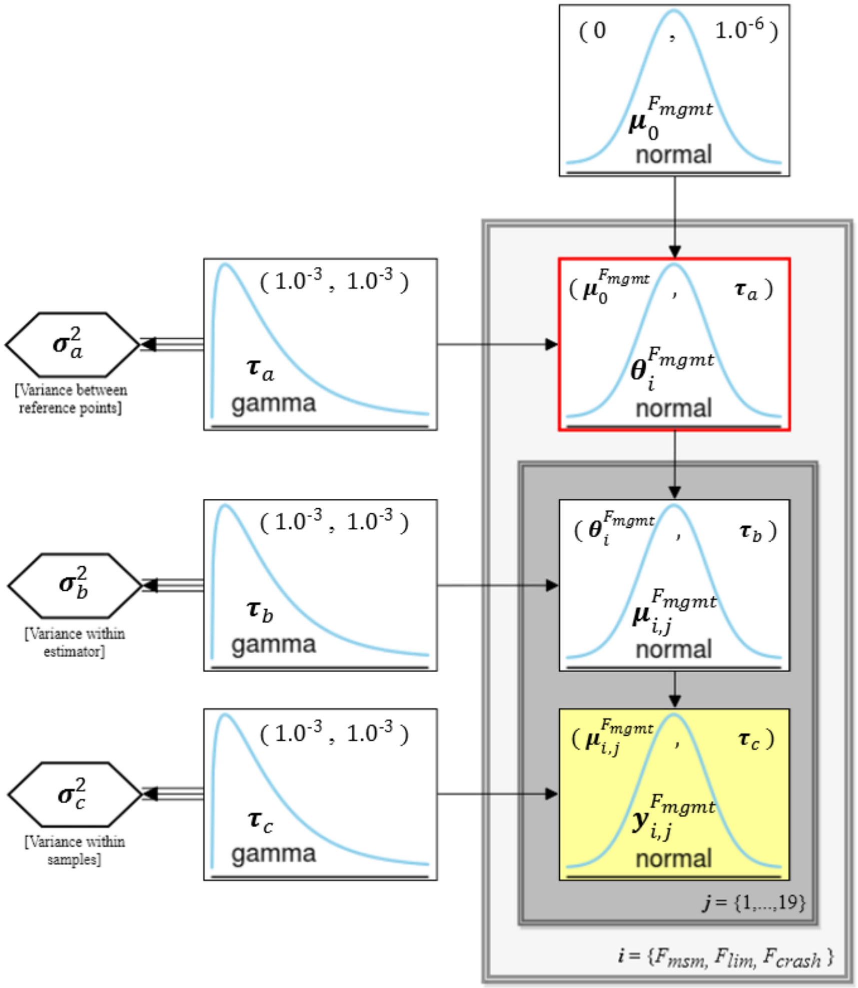


Figure 34a. Directed acyclic graph of the Bayesian hierarchical model for the derivation of biological reference points: F_{msm}, F_{lim}, F_{crash}.

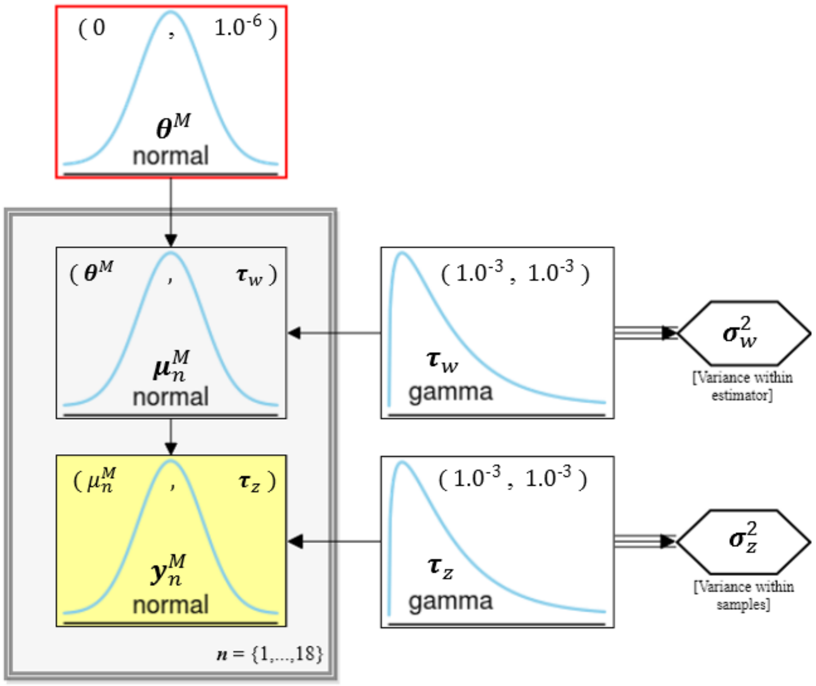


Figure 34b. Directed acyclic graph of the Bayesian hierarchical model for the derivation of Natural Mortality (M).

Table 14. Priors, observation distributions, and process functions of the of the Bayesian hierarchical model for the derivation of biological reference points (F_{msm} , F_{lim}, F_{crash}).

Model Equations	Descriptions / Selection Criteria	OpenBUGS equivalence script
Observation (Likelihood) Distributions [Yellow]		
$y_{i,j}^{F_{mgmt}} \sim \mathcal{N}(\mu_{i,j}^{F_{mgmt}}, \tau_c)$	Observation distribution populated by 3 pre-model observations (calculations) of F_{msm}, F_{lim}, and F_{crash} across (*i*=1, 2, 3 respectively) for each mgmt. ref point estimator (*j*=1…19).	`y_A[i , j] ~ dnorm(mu_A[i , j], Tau_within_A)`
Prior Probability Distributions		
$\mu_{i,j}^{F_{mgmt}} \sim \mathcal{N}(\theta_i^{F_{mgmt}}, \tau_b)$	Prior distribution for the mean of each F_{msm}, F_{lim}, and F_{crash} estimate within each of the 19 mgmt. ref. point estimators. Marginalization with respect to this node after appropriate simulations gives mean posterior estimates for every index coordinate or the mean for each individual observation.	`mu_A[i , j] ~ dnorm(mu_Fmgmt_A[i], Tau_A)`
$\theta_i^{F_{mgmt}} \sim \mathcal{N}(\mu_0^{F_{mgmt}}, \tau_a)$	Prior parameter of interest. Marginalization with respect to index (*i*=1, 2, 3) gives mean posteriors for biological reference points F_{msm}, F_{lim}, and F_{crash}.	`mu_Fmgmt_A[i] ~ dnorm(theta_A, Tau_btw_A)`
$\mu_0^{F_{mgmt}} \sim \mathcal{N}(0,1.0^{-6})$	Prior for mean of θ, which when marginalized is also equal to F_{lim}.	`theta_A ~ dnorm(0.0, 1.0E-6)`
$\tau_\alpha \sim \Gamma(1.0^{-3}, 1.0^{-3})$	Gamma distributions were included as priors for all precision (variance) parameters as they are both maximally uninformative and have expressly positive values (which mirrors real possible observations).	`Tau_btw_A ~ dgamma(0.001, 0.001)`
$\tau_b \sim \Gamma(1.0^{-3}, 1.0^{-3})$		`Tau_A ~ dgamma(0.001, 0.001)`
$\tau_c \sim \Gamma(1.0^{-3}, 1.0^{-3})$		`Tau_within_A ~ dgamma(0.001, 0.001)`
Process Functions		
$\sigma_a^2 = 1/\tau_a$	Basic reformulation of precision values (τ) as Variance (σ^2) for consistency of interpretation, albeit not expressly necessary for model validity.	`Variance_btw_A <- 1 / Tau_btw_A`
$\sigma_b^2 = 1/\tau_b$		`Variance_A <- 1 / Tau_A`
$\sigma_c^2 = 1/\tau_c$		`Variance_within_A <- 1 / Tau_within_A`

Table 15. Priors, observation distributions, and process functions of the of the Bayesian hierarchical model for the derivation natural mortality (M).

Model Equations	Descriptions / Selection Criteria	OpenBUGS equivalence script
Observation (Likelihood) Distributions [Yellow]		
$y_n^M \sim \mathcal{N}(\mu_n^M, \tau_z)$	Observation distribution populated by 18 pre-model observations (calculations) via the individual M estimators (*n*=1…18). *n* contingent on number of viable M estimators able to be calculated via specific vital parameter availability of species.	`y_B[n] ~ dnorm(mu_NatMort_B[n], Tau_within_B)`
Prior Probability Distributions		
$\mu_n^M \sim \mathcal{N}(\theta^M, \tau_w)$	Prior distribution for the mean of each of the 18 M estimators (*n* = 1…18).	`mu_NatMort_B[n] ~ dnorm(theta_B, Tau_btw_B)`
$\theta^M \sim \mathcal{N}(0,1.0^{-6})$	Prior parameter of interest. Marginalization gives posterior mean estimate of Natural Mortality (M).	`theta_B ~ dnorm(0.0, 1.0E-6)`
$\tau_w \sim \Gamma(1.0^{-3}, 1.0^{-3})$	Gamma distributions were included as priors for all precision (variance) parameters as they are both maximally uninformative (unbiased) and have expressly positive values (which mirrors real possible observations).	`Tau_btw_B ~ dgamma(0.001, 0.001)`
$\tau_z \sim \Gamma(1.0^{-3}, 1.0^{-3})$		`Tau_within_B ~ dgamma(0.001, 0.001)`
Process functions		
$\sigma_w^2 = {}^{1}/_{\tau_w}$	Basic reformulation of precision values (τ) as Variance (σ^2) for consistency of interpretation, albeit not expressly necessary for model validity	`Variance_btw_B <- 1 / Tau_btw_B`
$\sigma_z^2 = {}^{1}/_{\tau_z}$		`Variance_within_B <- 1 / Tau_within_B`

Joint Data Declaration for Joint Model Input Values

Table 16 houses the values input into the Bayesian hierarchical model. The design and presentation criteria are structurally identical to that which is given in the prior chapter (Chapter III); however, model dependent features were of course revised as necessary. One minor difference is that data for both models are included in a single table. Due to the fact that that both models were performed on the same run session, the data declaration is therefore carried out in a single step, and thus it is most logical to present these data values in a joint manner.

Table 16. Joint model data declaration: Bayesian hierarchical models for the derivation of biological reference points & natural mortality.

Component	Official Notation	OpenBUGS Equivalent Script	Exchange? (Yes/No) [a]	Value[b]	Data Acquisition Process
Structure Defining Values					
Plate Indices	J	mgmt_refpoint_ est_eqs_A	Depends*	= 19*	J = No. Ref point estimators (max 19)
	I	calculated_mgmt_ refpoint_types_A		= 3	I = No. Ref points per estimator (3)
	N	M_estimators_B		= 18*	N = No. Natural Mortality Estimator (max 18)
Stochastic Data					
Fmgmt Ref Point Values	$y_{i,j}^{F_{mgmt}}$	y_A	Y	=structure(.Data=c(0.06117, 0.0692, 0.08133, 0.07752, 0.07963, 0.08039, 0.06181, 0.09534, 0.04051, 0.06811, 0.04609, 0.10936, 0.16277, 0.06503, 0.08737, 0.09554, 0.06323, 0.05976, 0.06182, 0.09176, 0.1038, 0.122, 0.11627, 0.11944, 0.12058, 0.09271, 0.14301, 0.06077, 0.10216, 0.06913, 0.16403, 0.24415, 0.09755, 0.13105, 0.1433, 0.09485, 0.08964, 0.09273, 0.12234, 0.1384, 0.16266, 0.15503, 0.15925, 0.16078, 0.12362, 0.19068, 0.08102, 0.13621, 0.09218, 0.21871, 0.32553, 0.13007, 0.17473, 0.19107, 0.12646, 0.11953, 0.12364), .Dim=c(3,19))	Pre-model calculations for all (3) mgmt. reference points, i.e. {Fmsm, Flim, Fcrash}, as given per every possible estimator (max 19) linked via ω.
Natural Mortality Values	y_n^M	y_B	Y	=c(0.16878, 0.19837, 0.18906, 0.19421, 0.19607, 0.15075, 0.23254, 0.09881, 0.16611, 0.11241, 0.26672, 0.39699, 0.15862, 0.21309, 0.23302, 0.15422, 0.14576, 0.15078)	Pre-model calculations for all values of Natural Mortality given per every possible estimator of M (max 18).

[a] Refers to whether the set of data declaration values for a node, upon running the analysis for a new species, would be exchanged for distinct species-specific values or, alternatively, be retained, as they are values that are permanently necessary for effective calculation, irrespective of species. The answers are presented as yes or no (Y/N), affirming the need to exchange or negating the need to exchange relative to the particular shark species being analyzed. *The values in question are defined uniquely as "Depends" because the number of estimators, and thus J & N, may change, as they are dependent on the availability of vital parameter data, which is unqiue on a per species basis, but the value for I does not change, and therefore permanently remains =3.

[b] For the sake of example, values for *C. longimanus* are provided as stand-ins, though, if a different shark species were being analyzed, values would necessarily need to be exchanged in relavent categories as denoted by (Y) in the proceeding column, explained in note (a).

Combining Streams: Comparing Derived Values of F vs. F_{mgmt} for the Determination of Final Sustainability Status for the Effect of Longline Fishing on Regional Shark Stocks

Ultimately, the comparatively complex derivation of key study values, that of fishing mortality by longline bycatch in our region of interest for individual sharks (i.e., F) and corresponding biologically based management reference points $\{F_{msm}, F_{lim}, F_{crash}\}$, yields to a simple final step to produce the status determination for a specific species. The two values are entered into an inequality relationship; if F is greater than or, alternatively, less than the value threshold of a particular reference point, the species is designated as exhibiting the respective status condition affiliated with the outcome of such a comparison.

The relationships and corresponding status determinations between shark fishing Mortality (F) and corresponding set of biological reference points $\{F_{msm}, F_{lim}, F_{crash}\}$ is listed as follows. C*R*I stands for Credible Interval, the Bayesian analogue to the frequentist Confidence Interval and min[F_{mgmt}] equals the lower boundary for the range given by F_{mgmt} [±95% C*R*I]:

- Where $F < F_{msm}$, = Low-Risk (L; i.e. sustainable mortality);
- $F \geq \min[F_{msm}]$ *or* F + 95% Cr.I $\geq F_{msm}$, = Precautionary medium risk (m);
- $F_{msm} \leq F < F_{lim}$,= Medium risk (M);
- $F \geq \min[F_{lim}]$ *or* F + 95% Cr.I $\geq F_{lim}$, = Precautionary high risk (h);
- $F_{lim} \leq F < F_{crash}$, = High risk (H);
- $F \geq \min[F_{crash}]$ *or* F +95% Cr.I $\geq F_{crash}$, = Precautionary extreme high risk (e); and
- $F \geq F_{crash}$, = Extreme high risk (E).

As previously mentioned, the final step, and thus the core outcome of this research, is couched in simple graphical representation of this relationship, the cartesian location of the two data inputs being represented as an ordered pair: (F_{mgmt} [±95% $C_{R}I$], F [+95% $C_{R}I$]). The relation conditions between F and F_{mgmt} which prescribe the numerical basis for the determination of status designations were directly mapped to their equivalent cartesian regions on the graphical plane spread over three figures. Each graphical representation pivots around the boundary condition where F equals one of the three respective biological reference points.

Therefore, the coordinate position of the aforementioned ordered pair with relation the graphical feature (diagonal line) representing the boundary geometry at which $F = F_{mgmt}$ for each of the biological reference points $\{F_{msm}, F_{lim}, F_{crash}\}$ respectively, designates a final risk assessment description vis-à-vis the spatial bin (and thus status category) occupied by the ordered pair's graphical location.

Simply, the derived values of fishing mortality and appropriate reference point were combined in a single graphical representation, approximating an ordered pair with the probability space of analytical consequence denoted by range bars ("error bars"). The straightforward numerical juxtaposition of these two values, and most importantly the interpretive implications therein expressed by the nature of the arrangement, results in an explicit quantitative determination of status on a per species basis, a defined goal of my research venture.

Chapter V

Results

Figure 35 shows a small vantage of one dock, in one landing center, in one coastal city, in one state of India. A variety of craft are intermingled, as well as multiple gear-types and capacities represented. Although a formidable task, the results given below represent a novel, connective quantification of some portion of the impact rendered by hundreds or perhaps even thousands of similar scenes operating dynamically and daily around the vast, regional seas of continental India and its territorial islands.

Figure 35. Kasimedu fishing harbour (photo by author, Chennai. 2016)

Summary of Analytical Outcomes

Table 17 shows a list of individual species of shark that were party to this study's various analyses. The species is associated with both a scientific and common name, as well as a unique species number that is maintained across all related tables which host categorial information about individually assessed shark species within this study.

Table 17. Species numbering scheme reference key for entire study.

Sp. No.	Common name	Scientific name
1	Scalloped Hammerhead	*Sphyrna lewini*
2	Blue Shark	*Prionace glauca*
3	Silky Shark	*Carcharhinus falciformis*
4	Oceanic Whitetip	*Carcharhinus longimanus*
5	Tiger Shark	*Galeocerdo cuvier*
6	Dusky Shark	*Carcharhinus oscurus*
7	Common Thresher	*Alopias vulpinus*
8	Gulper Shark	*Centrophorus granulosus*
9	Crocodile Shark	*Pseudocarcharias kamoharai*
10	Great Hammerhead	*Sphyrna mokarran*
11	Shortfin Mako	*Isurus oxyrinchus*
12	Longfin Mako	*Isurus paucus*
13	Pelagic Thresher	*Alopias pelagicus*
14	Smoother Hammerhead	*Sphyrna zygaena*
15	Hardnose Shark	*Carcharhinus macloti*
16	Spinner Shark	*Carcharhinus brevipinna*
17	Bigeye Thresher	*Alopias superciliosus*
18	Silvertip Shark	*Carcharhinus albimarginatus*
19	Whitecheek Shark	*Carcharhinus dussumieri*
20	Sharpnose Sevengill Shark	*Heptranchias perlo*
21	Grey Reef Shark	*Carcharhinus amblyrhynchos*
22	Blacktip Shark	*Carcharhinus limbatus*
23	Milk Shark	*Rhizoprionodon acutus*
24	Spot-tail Shark	*Carcharhinus sorrah*
25	Sandbar Shark	*Carcharhinus plumbeus*
26	Spadenose Shark	*Scliodion laticaudus*
27	Blacktip Reef Shark	*Carcharhinus melanopterus*
28	Zebra Shark	*Stegostoma fasciatum*
29	Broadfin Shark	*Lamiopsis temmincki*
30	Sliteye Shark	*Loxodon macrorhinus*
31	Pondicherry Shark	*Carcharhinus hemidon*

This number may, in effect, act as a shorthand reference to the particular species and it is maintained ubiquitously over all tables which reference values for this study's set of focus shark species, which is many. (i.e., species No.1 always refers to Scalloped Hammerhead in every relevant table within this study, without the scientific or common name of the shark explicitly needing to be given.). The remaining table-wise organizational structure within this section adheres to the following conventions:

Model (I) Outputs: Bayesian Hierarchical Model for the Derivation Shark Fishing Mortality (F)

For concision and clarity, the Bayesian hierarchical model for the derivation shark fishing mortality (F) (see Chapter III) is referred to as Model (I), the outputs of which are scaffolded across Table 18, parts a–e.

The primary intent of Model (I) was the derivation of bycatch (F for individual shark species) and is referred to consistently as the "Bayesian hierarchical model for the derivation shark fishing mortality." Due to this primacy, marginal posterior estimates of the means of various other parameters of secondary interest were available for calculation via Model (I) as well and are expressly derived. However, given the bulk of numerical outputs in relation to this model, only those deemed most relevant are given in this chapter while the remainder are given only in Ancillary Appendix 3 and only for select species. Additionally, total goodness-of-fit statistics for the model, relevant to species specific runs where available, fall within this scope of total model (I) outputs. Thus, Table 18 presents all relevant Model (I) outputs and is divided into five sections, Tables 18[a–e]. The contents of Table 18's sections are:

- Effective for the time period (2010-’14), both for individual years (Table 18b) and as a five-year grand mean thereof (Table 18a), fishing mortality (F) marginal posterior means for (30) species of sharks were produced;
- Marginal posterior mean for area of effective longline impact for 30 species (Table 18d) for the 5-year time period in question;
- Marginal posterior means for all three catch mechanism parameters $\{\zeta^{\text{Encounterability}}, \zeta^{\text{Selectivity}}, \zeta^{\text{Post-Capture Mortality}}\}$ (Table 18c);
- Year-wise marginal posterior means of Yellowfin Tuna Fishing Mortality (F) in the IOTC competence area (Ancillary Appendix 3) and thus for the Indian Oceanic EEZ by proxy;
- Year-wise marginal posterior means for longline YFT Catch (C) within the Indian Oceanic EEZ (Ancillary Appendix 3);
- Marginal posterior for 5-year grand mean for longline YFT Catch (C) within the Indian Oceanic EEZ (Ancillary Appendix 3);
- Marginal posterior for 5-year grand mean for total (i.e. all gear) YFT Catch (C) within the Indian Ocean Tuna Commission Competence area (Ancillary Appendix 3);
- Total goodness-of-fit statistics (D_{bar}, D_{hat}, DIC, pD) for model (I) for selected species (Table 18e);
- Credible Intervals (Cr. I) [±95%] for all assessed parameters’ marginal posterior distributions.

Table 18a. Marginal posterior means, credible intervals, and other summary statistics of average fishing mortality in India's oceanic EEZ by species over years [2010-'14].

				Cr. I						
No.	$\hat{\mu}_F^{\omega}$	*SD*	MC error	2.5%	5.0%	10.0%	median	90.0%	95.0%	97.5%
1	**0.0450**	1.40E-02	1.19E-04	0.0164	0.0216	0.0274	0.0452	0.0622	0.0677	0.0728
2	**0.1852**	1.83E-02	9.44E-05	0.1489	0.1552	0.1622	0.1852	0.2081	0.2150	0.2214
3	**0.1928**	2.03E-02	1.28E-04	0.1521	0.1592	0.1672	0.1929	0.2182	0.2257	0.2325
4	**0.1680**	1.77E-02	7.85E-05	0.1329	0.1389	0.1457	0.1680	0.1902	0.1969	0.2030
5	**0.1011**	1.87E-02	1.26E-04	0.0636	0.0706	0.0780	0.1011	0.1241	0.1316	0.1386
6	**0.0479**	1.43E-02	1.03E-04	0.0182	0.0237	0.0299	0.0482	0.0654	0.0709	0.0761
7	**0.0863**	1.71E-02	1.17E-04	0.0520	0.0585	0.0653	0.0863	0.1072	0.1140	0.1203
8	**0.0983**	1.95E-02	9.12E-05	0.0578	0.0659	0.0742	0.0987	0.1218	0.1290	0.1358
9	**0.1263**	2.12E-02	1.18E-04	0.0790	0.0892	0.0995	0.1280	0.1512	0.1576	0.1634
10	**0.1106**	1.87E-02	1.88E-04	0.0732	0.0800	0.0874	0.1106	0.1338	0.1412	0.1479
11	**0.1768**	1.78E-02	9.21E-05	0.1416	0.1478	0.1546	0.1768	0.1989	0.2057	0.2120
12	**0.0902**	1.64E-02	1.16E-04	0.0571	0.0634	0.0700	0.0903	0.1105	0.1169	0.1228
13	**0.1608**	1.54E-02	6.01E-05	0.1303	0.1357	0.1416	0.1608	0.1800	0.1858	0.1913
14	**0.1858**	1.83E-02	7.05E-05	0.1496	0.1560	0.1630	0.1858	0.2086	0.2157	0.2221
15	**0.1649**	2.73E-02	1.54E-04	0.1041	0.1174	0.1308	0.1671	0.1968	0.2051	0.2126
16	**0.1589**	2.65E-02	1.51E-04	0.0999	0.1126	0.1256	0.1610	0.1899	0.1980	0.2051
17	**0.1703**	1.74E-02	7.43E-05	0.1360	0.1420	0.1486	0.1703	0.1922	0.1988	0.2047
18	**0.1654**	2.59E-02	1.39E-04	0.1083	0.1205	0.1328	0.1672	0.1962	0.2042	0.2114
19	**0.0825**	1.54E-02	8.13E-05	0.0491	0.0561	0.0633	0.0834	0.1008	0.1059	0.1106
20	**0.0908**	1.87E-02	8.64E-05	0.0521	0.0600	0.0678	0.0912	0.1132	0.1203	0.1270
21	**0.1688**	2.68E-02	1.47E-04	0.1097	0.1224	0.1352	0.1708	0.2002	0.2085	0.2159
22	**0.1384**	2.38E-02	1.25E-04	0.0875	0.0979	0.1086	0.1395	0.1670	0.1751	0.1825
23	**0.1438**	2.44E-02	1.32E-04	0.0911	0.1020	0.1133	0.1451	0.1731	0.1813	0.1886
24	**0.1195**	2.17E-02	1.17E-04	0.0727	0.0824	0.0923	0.1207	0.1455	0.1527	0.1591
25	**0.0212**	1.11E-02	1.30E-04	0.0023	0.0041	0.0070	0.0207	0.0356	0.0403	0.0448
26	**0.0972**	1.92E-02	9.57E-05	0.0579	0.0657	0.0737	0.0974	0.1204	0.1279	0.1349
27	**0.1438**	2.45E-02	1.33E-04	0.0910	0.1020	0.1132	0.1451	0.1731	0.1813	0.1887
28	**0.1113**	2.39E-02	1.16E-04	0.0613	0.0714	0.0818	0.1118	0.1402	0.1491	0.1575
29	**0.1334**	2.23E-02	1.10E-04	0.0848	0.0953	0.1058	0.1347	0.1597	0.1673	0.1741
30	**0.1115**	2.09E-02	1.01E-04	0.0675	0.0764	0.0856	0.1123	0.1365	0.1440	0.1509
31	**Unknown**									

Table 18b. Marginal posterior means and credible intervals for shark F by year [2010-2014].

	Post. Mean	Cr. I		Post. Mean	Cr. I		Post. Mean	Cr. I		Post. Mean	Cr. I		Post. Mean	Cr. I	
No.	*2010*	2.5%	97.5%	*2011*	2.5%	97.5%	*2012*	2.5%	97.5%	*2013*	2.5%	97.5%	*2014*	2.5%	97.5%
1	0.0511	0.0184	0.0835	0.0360	0.0129	0.0595	0.0363	0.0118	0.0612	0.0572	0.0196	0.0954	0.0445	0.0154	0.0748
2	0.2008	0.1569	0.2459	0.1823	0.1419	0.2244	0.1569	0.1026	0.1992	0.1792	0.1265	0.2270	0.2066	0.1514	0.2620
3	0.2090	0.1608	0.2577	0.1616	0.1231	0.2012	0.1587	0.1034	0.2028	0.2056	0.1448	0.2610	0.2290	0.1667	0.2915
4	0.1832	0.1410	0.2263	0.1583	0.1211	0.1966	0.1410	0.0915	0.1806	0.1642	0.1146	0.2094	0.1932	0.1403	0.2466
5	0.1143	0.0709	0.1588	0.0787	0.0480	0.1111	0.0806	0.0438	0.1160	0.1287	0.0752	0.1828	0.1031	0.0605	0.1477
6	0.0538	0.0202	0.0864	0.0383	0.0143	0.0622	0.0387	0.0132	0.0642	0.0604	0.0216	0.0990	0.0484	0.0174	0.0798
7	0.0906	0.0535	0.1284	0.0838	0.0494	0.1192	0.0726	0.0380	0.1061	0.0838	0.0461	0.1221	0.1008	0.0571	0.1461
8	0.1090	0.0632	0.1529	0.0832	0.0477	0.1181	0.0823	0.0421	0.1194	0.1259	0.0690	0.1802	0.0908	0.0498	0.1314
9	0.1246	0.0765	0.1646	0.0970	0.0591	0.1291	0.0959	0.0522	0.1306	0.1319	0.0763	0.1783	0.1820	0.1090	0.2441
10	0.1216	0.0791	0.1652	0.0993	0.0639	0.1362	0.0925	0.0525	0.1299	0.1089	0.0655	0.1524	0.1304	0.0808	0.1819
11	0.1921	0.1495	0.2359	0.1668	0.1292	0.2060	0.1484	0.0969	0.1891	0.1729	0.1216	0.2194	0.2037	0.1489	0.2588
12	0.0902	0.0557	0.1252	0.0713	0.0437	0.1001	0.0825	0.0452	0.1179	0.0540	0.0306	0.0774	0.1532	0.0931	0.2138
13	0.1549	0.1217	0.1891	0.1147	0.0891	0.1413	0.1113	0.0741	0.1405	0.1708	0.1232	0.2140	0.2522	0.1918	0.3131
14	0.2013	0.1573	0.2465	0.1811	0.1409	0.2227	0.1572	0.1027	0.1996	0.1794	0.1266	0.2271	0.2100	0.1538	0.2661
15	0.2076	0.1297	0.2712	0.1340	0.0823	0.1780	0.1282	0.0695	0.1744	0.2003	0.1171	0.2694	0.1544	0.0907	0.2095
16	0.2056	0.1278	0.2688	0.1317	0.0805	0.1752	0.1224	0.0662	0.1668	0.1964	0.1143	0.2646	0.1383	0.0807	0.1885

(cont.)

17	0.1896	0.1472	0.2334	0.1609	0.1241	0.1992	0.1451	0.0944	0.1852	0.1653	0.1159	0.2103	0.1908	0.1390	0.2433
18	0.1867	0.1203	0.2427	0.1225	0.0779	0.1616	0.1289	0.0731	0.1735	0.2162	0.1324	0.2871	0.1727	0.1061	0.2315
19	0.0674	0.0390	0.0930	0.0129	0.0073	0.0181	0.0585	0.0304	0.0824	0.1233	0.0697	0.1703	0.1506	0.0871	0.2064
20	0.0986	0.0557	0.1399	0.0731	0.0409	0.1051	0.0750	0.0376	0.1099	0.1169	0.0628	0.1692	0.0903	0.0486	0.1319
21	0.1889	0.1209	0.2458	0.1269	0.0801	0.1675	0.1314	0.0740	0.1771	0.2193	0.1332	0.2916	0.1774	0.1083	0.2381
22	0.1798	0.1124	0.2397	0.1199	0.0737	0.1628	0.1080	0.0586	0.1503	0.1681	0.0979	0.2312	0.1160	0.0678	0.1614
23	0.1802	0.1130	0.2391	0.1185	0.0730	0.1601	0.1146	0.0627	0.1584	0.1729	0.1013	0.2362	0.1327	0.0781	0.1833
24	0.1181	0.0704	0.1606	0.1206	0.0720	0.1639	0.1020	0.0539	0.1426	0.1348	0.0758	0.1871	0.1222	0.0697	0.1705
25	0.0195	0.0021	0.0416	0.0084	0.0009	0.0180	0.0116	0.0011	0.0253	0.0313	0.0032	0.0674	0.0354	0.0037	0.0759
26	0.1316	0.0777	0.1840	0.0899	0.0521	0.1282	0.0752	0.0385	0.1099	0.1150	0.0629	0.1663	0.0740	0.0406	0.1084
27	0.1877	0.1176	0.2491	0.1216	0.0747	0.1643	0.1114	0.0604	0.1542	0.1752	0.1024	0.2395	0.1231	0.0720	0.1703
28	0.1127	0.0601	0.1638	0.1110	0.0601	0.1599	0.0945	0.0445	0.1408	0.1255	0.0636	0.1850	0.1126	0.0573	0.1667
29	0.1318	0.0823	0.1756	0.0821	0.0504	0.1111	0.0916	0.0506	0.1260	0.1801	0.1079	0.2430	0.1814	0.1103	0.2453
30	0.1414	0.0846	0.1932	0.0920	0.0541	0.1282	0.0858	0.0448	0.1222	0.1386	0.0777	0.1949	0.0996	0.0560	0.1416
31	**Unknown**														

Table 18c. Pre-model values, uniform prior ranges & marginal posterior means of catch mechanism variables: qih, qiλ, PcMi.

	Param Val. [Uni. Prior Rng.]	Post. Mean	Cr. I		Param Val. [Uni. Prior Rng.]	Post. Mean	Cr. I		Param Val. [Uni. Prior Rng.]	Post. Mean	Cr. I	
No.	qih^{a}	$\zeta^{Encnt.}$	2.5%	97.5%	qiλ^{a}	$\zeta^{Select.}$	2.5%	97.5%	PcMi^{a}	ζ^{PcM}	2.5%	97.5%
1	0.999 –	0.9990	0.9963	1.0000	0.246 –	0.2399	0.0825	0.4362	0.875 –	0.8719	0.5915	0.9961
2	0.999 –	0.9990	0.9963	1.0000	0.996 –	0.9960	0.9850	0.9999	0.984 –	0.9844	0.9436	0.9996
3	0.999 –	0.9990	0.9963	1.0000	0.925 –	0.9288	0.7761	0.9978	0.99 –	0.9899	0.9636	0.9997
4	0.999 –	0.9990	0.9963	1.0000	0.939 –	0.9417	0.8095	0.9983	0.974 –	0.9742	0.9102	0.9993
5	0.999 –	0.9990	0.9963	1.0000	0.521 –	0.5416	0.3110	0.8349	0.903 –	0.8964	0.6687	0.9969
6	0.999 –	0.9990	0.9963	1.0000	0.245 –	0.2405	0.0888	0.4084	0.999 –	0.9737	0.9061	0.9993
7	0.999 –	0.9990	0.9963	1.0000	0.562 –	0.5894	0.3226	0.9144	0.825 –	0.8197	0.5127	0.9929
8	0.666 [0.333-.8325]	0.6866	0.3571	0.9777	0.666 [0.333-1.000]	0.7708	0.4002	0.9967	0.999 [0.666-1.000]	0.8565	0.5115	0.9984
9	0.8325 [0.666-1.000]	0.8907	0.6219	0.9986	0.999 [0.333-1.000]	0.8907	0.6217	0.9986	0.999 [0.666-1.000]	0.9162	0.6880	0.9990
10	0.999 –	0.9990	0.9963	1.0000	0.622 –	0.6500	0.4068	0.9155	0.999 –	0.9990	0.9963	1.0000

(cont.)

11	0.999 –	0.9990	0.9963	1.0000	0.97 –	0.9704	0.8968	0.9992	0.994 –	0.9941	0.9783	0.9999
12	0.999 –	0.9990	0.9963	1.0000	0.6 –	0.6273	0.3748	0.9039	0.992 –	0.9920	0.9705	0.9998
13	0.999 –	0.9990	0.9963	1.0000	0.997 –	0.9970	0.9888	0.9999	0.999 –	0.9990	0.9963	1.0000
14	0.999 –	0.9990	0.9963	1.0000	0.997 –	0.9970	0.9889	0.9999	0.997 –	0.9970	0.9888	0.9999
15	0.8325 [0.333-1.000]	0.8909	0.6241	0.9987	0.999 [0.333-1.000]	0.8926	0.6332	0.9987	0.999 [0.666-1.000]	0.9157	0.6915	0.9990
16	0.8325 [0.333-1.000]	0.8917	0.6276	0.9986	0.999 [0.333-1.000]	0.8915	0.6211	0.9987	0.999 [0.666-1.000]	0.9172	0.6958	0.9990
17	0.999 –	0.9990	0.8926	0.9992	0.968 –	0.9690	0.9963	1.0000	0.97 –	0.9705	0.8951	0.9992
18	0.8325 [0.333-1.000]	0.9008	0.6547	0.9987	0.999 [0.333-1.000]	0.9008	0.6547	0.9987	0.999 [0.666-1.000]	0.9166	0.6947	0.9990
19	0.8325 [0.333-1.000]	0.8456	0.5264	0.9978	0.8325 [0.333-1.000]	0.8453	0.5256	0.9979	0.999 [0.666-1.000]	0.8912	0.6186	0.9987
20	0.4995 [0.333-.8325]	0.6674	0.3376	0.9757	0.8325 [0.333-1.000]	0.7578	0.3770	0.9965	0.999 [0.666-1.000]	0.8513	0.4962	0.9984
21	0.8325 [0.333-1.000]	0.8930	0.6351	0.9986	0.999 [0.333-1.000]	0.8917	0.6305	0.9987	0.999 [0.666-1.000]	0.9164	0.6931	0.9990
22	0.666 [0.333-1.000]	0.8458	0.5375	0.9979	0.999 [0.333-1.000]	0.8467	0.5387	0.9979	0.999 [0.666-1.000]	0.8899	0.6175	0.9988

(cont.)

23	0.8325 [0.333-1.000]	0.8567	0.5569	0.9982	0.8325 [0.333-1.000]	0.8551	0.5536	0.9980	0.999 [0.666-1.000]	0.8952	0.6356	0.9988
24	0.8325 [0.333-1.000]	0.8514	0.5420	0.9980	0.8325 [0.333-1.000]	0.8520	0.5405	0.9980	0.999 [0.666-1.000]	0.8940	0.6260	0.9988
25	0.999 –	0.9990	0.9963	1.0000	0.172 –	0.1516	0.0162	0.3301	0.999 –	0.9990	0.9963	1.0000
26	0.4995 [0.333-1.000]	0.7308	0.3590	0.9957	0.8325 [0.333-1.000]	0.7324	0.3609	0.9957	0.999 [0.666-1.000]	0.8393	0.4728	0.9983
27	0.8325 [0.333-1.000]	0.8564	0.5566	0.9980	0.8325 [0.333-1.000]	0.8570	0.5586	0.9981	0.999 [0.666-1.000]	0.8953	0.6331	0.9988
28	0.4995 [0.333-.8325]	0.7024	0.3705	0.9783	0.999 [0.333-1.000]	0.8197	0.4654	0.9977	0.999 [0.666-1.000]	0.8631	0.5309	0.9985
29	0.666 [0.333-.8325]	0.8628	0.5649	0.9982	0.999 [0.333-1.000]	0.7953	0.5078	0.9877	0.999 [0.666-1.000]	0.8989	0.6420	0.9988
30	0.666 [0.333-.8325]	0.7453	0.4347	0.9834	0.8325 [0.333-1.000]	0.8204	0.4822	0.9976	0.999 [0.666-1.000]	0.8788	0.5791	0.9986
31	**Unknown**											

[a] Specific values for qih, qiλ, and PcMi (which in this model are incorporated via a somewhat uncommon mean-wise (μ) parameterization of a beta distribution, as opposed to the standard [α, β] parameterization) may be drawn from literature (primarily Murua et al., 2012) and entered as a constant for the corresponding beta distribution's (μ) parameter. When a catch mechanism variable for a particular species has, however, not been explicitly measured and published in relevant literature, a feasible min/max bounded estimate of the variable's range is produced, the values for which are drawn from this study's risk scoring system for otherwise unknown values of catch mechanism variables (see Chapter II for scoring system process and criteria). When, due to the aforementioned circumstances, is has been necessary to furnish a min/max range estimate for a species, a uniform prior distribution is used to model the (μ) parameter of the beta distribution [which would otherwise simply take a constant value], and the min/max values for the estimated range are entered as the hyperparameters of the uniform prior distribution, (a, b) respectively.

Range estimates—and thus the hyperparameters (a, b) for the uniform prior on the corresponding Beta distribution's (μ) parameter—are contained herein. They are only given within a table cell, however, when no published values were available. Although an estimated range min/max furnished for species defined as such is given, a singular, pre-model value of qih, qiλ, and PcMi had to also be produced for the calculation of pre-model F, even when the species did not have a preexisting, published value for the specific catch mechanism variable. In that vein, two values are provided for these species, and included in relevant cells: 1) the utilized, singular pre-model value for the calculation of pre-model F and 2) values of for a prospective min/max range estimate, utilized as the constant values for the (a, b) hyperparameters of the prior uniform distribution on the (μ) parameter of the Beta distribution modeling its respective catch mechanism variable. However, in cases where when a published value for a catch mechanism variable *could be located*, the same value was utilized for both the singular value necessary for the pre-model calculation of F and for the single value used as the constant entered as the (μ) parameter for the catch mechanism variable's Beta distribution in the Bayesian calculation for F, and thus is the reason why only one value is posited in relevant cells for these species.

Implications of some derived bycatch fishing mortality values. Broadly speaking, F values for most of the 30 species are likely the first values reported for the Indian Ocean and almost certainly for the Indian Exclusive Economic Zone (Tables 18a & 18b). Moreover, a number of little known, semi-coastal North Indian Ocean-rim /west Indo-Pacific endemic sharks where adequately eligible for inclusion using the methods herein explored and represent among the first fisheries related outputs of the Broadfin shark (*Lamiopsis temminckii*; ICUN Endangered), and perhaps the somewhat better known Whitecheek Shark (*Carcharhinus dussumieri;* ICUN Near Threatened), but important for the Indian context regarding both species. Additionally, fishing mortality (F) rate analyses for a number of mid- to deep-water specialist species are also furnished (Tables 18a & 18b): the Crocodile Shark (*Pseudocarcharias kamoharai*), Sharpnose sevengill (*Heptranchias perlo*), and Gulper Shark (*Centrophorus granulosus*). Together, these species entail an unexpected cluster contribution, albeit modest, to the improved understanding of fisheries impact occurring in the deeper bathymetric zones within these regional seas, which historically have been little known or managed and harbors very limited recovery potential even to comparatively modest modern fishing pressures (Simpfendorfer & Kyne, 2009).

Table 18d. Marginal posterior means of area of effective fishing impact over years [2010-'14].

	Posterior Mean	Cr. I		[%] Species Habitat Distribution within Indian Oceanic EEZ subject to LL Fishing Impact
No.	$\mu^{\varepsilon}_{Aif_0}$	2.5%	97.5%	
1	110596	59207	161837	43.36
2	626285	313880	939575	37.12
3	299130	169861	428045	40.33
4	559025	291431	826295	35.76
5	92070	50209	134048	41.69
6	81568	44368	118708	40.41
7	441615	231221	651065	36.54
8	169448	89503	249275	45.39
9	199214	132131	266090	30.67
10	438075	232932	642805	34.11
11	549290	286858	812135	35.71
12	30061	16030	44103	27.65
13	240278	170687	309750	28.72
14	555780	282079	829245	36.65
15	75343	35282	115286	42.86
16	63809	28081	99445	41.63
17	574660	289867	858450	35.60
18	87645	48469	126703	41.51
19	10304	4643	15957	20.51
20	124579	69355	179803	44.03
21	95049	53100	137087	42.52
22	73780	31860	115788	43.74
23	84223	39501	128915	43.32
24	66552	34987	98147	36.29
25	19980	12178	27836	23.60
26	73839	28574	119269	48.23
27	66965	29022	104991	43.67
28	66582	35017	98265	46.37
29	25520	17036	33984	38.44
30	68381	31270	105463	42.14
31	**Unknown**			

Note. In column 2, 3 and 4, the unit for the value given is km^2.

Table 18e. Total goodness-of-fit statistics (DIC)* for Model (I), selected species.

No.	Dbar	Dhat	DIC	pD
1	39.95	19.46	60.44	20.49
2	70.83	51.20	90.46	19.63
3	61.81	42.08	81.55	19.74
4	67.80	48.09	87.51	19.71
5	43.55	23.05	64.05	20.50
6	37.03	16.53	57.54	20.50
7	58.45	38.01	78.88	20.44
8				
9				
10				
11	68.23	48.57	87.89	19.66
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25	18.42	-1.91	38.75	20.30
26	45.87	25.35	66.39	20.52
27	48.82	28.45	69.18	20.37
28	45.47	24.87	66.08	20.60
29				
30				
31				

Note. DIC and other related statistics are not performed for all species regarding the final/most up to date model—however, a representative sample has been furnished to showcase a fairly broad range of reactions to the model based upon core data tropes, frequently expressed along the lines of species subgroupings with similar data characteristics. Generally speaking, relatively similar (although not exactly identical) model performance across species was observed. Better fits occur [evident via lower DIC values] with species with smaller maximum operative ranges w/in the FJA and/or espouse lower catch mechanism variable values [on a scale from 0–1] for any number of possible reasons; i.e., an interpretation of this is such that the F of species with more specific catch profiles or a more specific "hit" condition furnishes better model fitness, which is logical.
*DIC=Deviance Information Criterion.

Model (II) Outputs: Bayesian Hierarchical Model for the Derivation of Shark Biological Reference Points (F_{msm}, F_{lim}, F_{crash})

The Bayesian hierarchical model for the derivation of biological reference points (F_{msm}, F_{lim}, F_{crash}) (see Chapter IV) I here refer to as Model (II), the outputs of which are scaffolded across Table 19, a and b.

The same long-form naming convention, existence of secondary parameters of interest outside of the primary, titular parameter, and output of goodness-of-fit statistics are all represented in Model (II) in a similar convention as was described in Model (I); however, the number of parameters of secondary interest is much fewer in the case of model (II). Thus, Table 19 is concerned with all relevant Model (II) outputs and is divided into two sections:

- Marginal posterior means for biological-based management reference points $\{F_{msm}, F_{lim}, F_{crash}\}$ for 17 (of 30) species (Table 19a);
- Marginal posterior variance both *within* samples and *between* management reference points (Table 19b);
- Total goodness-of-fit statistics (D_{bar}, D_{hat}, DIC, pD) for Model (II) for selected species (Table 19b);
- Credible Intervals [±95%] for all assessed parameters' marginal posterior distributions.

Table 19a. Marginal posterior means & credible intervals for management reference points: F_{msm}, F_{lim}, and F_{crash}.

	Posterior Mean	Cr. I		**Posterior Mean**	Cr. I		**Posterior Mean**	Cr. I	
No.	$\boldsymbol{\theta}_{\mathbf{Fmsm}}$	2.5%	97.5%	$\boldsymbol{\theta}_{\mathbf{Flim}}$	2.5%	97.5%	$\boldsymbol{\theta}_{\mathbf{Fcrash}}$	2.5%	97.5%
1	**0.0606**	0.0512	0.0700	**0.0904**	0.0811	0.0998	**0.1202**	0.1108	0.1296
2	**0.1067**	0.0831	0.1304	**0.1571**	0.1338	0.1803	**0.2074**	0.1837	0.2309
3	**0.0632**	0.0523	0.0741	**0.0941**	0.0833	0.1050	**0.1250**	0.1141	0.1359
4	**0.0787**	0.0586	0.0989	**0.1158**	0.0959	0.1357	**0.1527**	0.1326	0.1728
5	**0.0770**	0.0601	0.0939	**0.1138**	0.0971	0.1305	**0.1506**	0.1337	0.1675
6	**0.0393**	0.0286	0.0501	**0.0584**	0.0477	0.0691	**0.0774**	0.0667	0.0882
7	**0.0794**	0.0578	0.1011	**0.1164**	0.0951	0.1377	**0.1534**	0.1318	0.1749
8	**0.0652**	0.0428	0.0877	**0.0950**	0.0729	0.1170	**0.1247**	0.1022	0.1471
9									
10	**0.0552**	0.0430	0.0675	**0.0820**	0.0698	0.0941	**0.1087**	0.0964	0.1209
11	**0.0557**	0.0450	0.0665	**0.0829**	0.0722	0.0936	**0.1101**	0.0993	0.1208
12	**0.0457**	0.0326	0.0589	**0.0677**	0.0547	0.0807	**0.0896**	0.0764	0.1027
13	**0.0594**	0.0491	0.0697	**0.0885**	0.0783	0.0988	**0.1176**	0.1073	0.1279
14	**0.0743**	0.0587	0.0900	**0.1100**	0.0946	0.1255	**0.1457**	0.1301	0.1613
15									
16	**0.0737**	0.0622	0.0852	**0.1098**	0.0984	0.1212	**0.1459**	0.1344	0.1573
17	**0.0561**	0.0416	0.0707	**0.0830**	0.0685	0.0974	**0.1098**	0.0953	0.1243
18									
19									
20									
21									
22	**0.1088**	0.0860	0.1317	**0.1605**	0.1380	0.1830	**0.2121**	0.1892	0.2349
23									
24	**0.1922**	0.1408	0.2445	**0.2783**	0.2285	0.3281	**0.3641**	0.3119	0.4155

Note. For boxplots and density strip graphic presentation of the F_{mgmt} marginal posterior distributions, see Ancillary Appendix 2. In Table 19a, Table 19b, and Table 20, spp. nos. 9, 15, 18-21, 23, and 25-31 were not calculated within the context of this study and are thus greyed out or not included within this suite of tables for the aforementioned reason.

Table 19b. Marginal posterior means and credible intervals of variance parameters for mgmt. reference points & total model goodness-of-fit measurements for model (II).

	Posterior Mean	Cr. I		Posterior Mean	Cr. I		Model Goodness of Fit Statistics [Deviance Information Criterion (DIC)]			
No.	* σ_c^2	2.5%	97.5%	** σ_a^2	2.5%	97.5%	Dbar	Dhat	DIC	pD
1	2.17E-04	1.16E-04	3.70E-04	2.29E-02	5.09E-04	7.58E-02	-331.7	-363.4	-300.1	31.63
2	1.36E-03	3.62E-04	2.78E-03	4.48E-02	8.99E-04	1.46E-01	-223.6	-255.6	-191.5	32.04
3	2.92E-04	1.46E-04	5.13E-04	2.39E-02	5.24E-04	7.88E-02	-312.6	-344.2	-280.9	31.65
4	1.00E-03	3.14E-04	1.98E-03	2.88E-02	6.13E-04	9.75E-02	-240.5	-272.3	-208.6	31.89
5	7.01E-04	2.61E-04	1.34E-03	2.83E-02	6.18E-04	9.56E-02	-260.4	-292.2	-228.6	31.79
6	2.86E-04	1.44E-04	5.00E-04	1.61E-02	3.70E-04	5.49E-02	-313.9	-345.6	-282.3	31.63
7	1.15E-03	3.38E-04	2.31E-03	2.90E-02	6.10E-04	9.80E-02	-232.7	-264.6	-200.8	31.91
8	1.26E-03	3.53E-04	2.54E-03	2.44E-02	4.91E-04	7.99E-02	-227.9	-259.7	-196	31.88
9										
10	3.68E-04	1.73E-04	6.60E-04	2.11E-02	4.61E-04	6.96E-02	-298.3	-330	-266.6	31.68
11	2.84E-04	1.43E-04	4.97E-04	2.12E-02	4.68E-04	7.02E-02	-314.3	-346	-282.7	31.64
12	4.05E-04	1.84E-04	7.38E-04	2.28E-02	4.00E-04	5.99E-02	-277.5	-307.6	-247.4	30.12
13	2.61E-04	1.34E-04	4.53E-04	2.25E-02	4.97E-04	7.43E-02	-319.7	-351.3	-288.1	31.63
14	6.00E-04	2.37E-04	1.13E-03	3.09E-02	5.99E-04	9.15E-02	-269.5	-301.2	-237.7	31.77
15										
16	3.24E-04	1.58E-04	5.72E-04	2.71E-02	6.14E-04	9.20E-02	-306.3	-337.9	-274.6	31.67
17	5.22E-04	2.17E-04	9.68E-04	2.06E-02	4.59E-04	6.98E-02	-277.5	-309.2	-245.8	31.71
18										
19										
20										
21										
22	1.28E-03	3.55E-04	2.59E-03	4.62E-02	9.36E-04	1.51E-01	-226.9	-258.9	-194.9	31.97
23										
24	6.42E-03	6.16E-04	1.48E-02	1.11E-01	1.87E-03	3.60E-01	-143.1	-172.2	-114	29.12

Note. Model goodness of fit statistics for this model (Model II) are included in a combined fashion within this table for ease of representation. In the previous Bayesian hierarchical model (for the derivation of shark Fishing Mortality, Model I), operative in the evaluation of the derivation of additional parameters (such as those in in Tables 18[a-d]), model goodness of fit statistics were included as a separate table in order to clearly identify that the values applied to the entirety of the model, not just any specific marginal parameter; though, strictly speaking, this should be evident purely through the intrinsic nature of the feature, never the less they were placed alone for added intuition.

* The parameter σ_c^2 models variance *within* samples

** The parameter σ_a^2 models variance *between* reference points.

Model (III) Outputs: Bayesian Hierarchical Model for the Derivation of Natural Mortality

The Bayesian Hierarchical Model for the Derivation of Natural Mortality (M) (see Chapter IV) is here referred to as Model (III), the outputs of which are given in Table 20.

Strictly speaking, in terms of coding protocol, Model (III) exists as an isolated full hierarchical model run simultaneously with Model (II) for the purposes of computational convenience. This pure technicality aside, theoretically speaking, the model is rendered as a completely independent mathematical entity and is thus unequivocally a fully separate Bayesian hierarchical model. Given its addendum status however, it has not been bannered as a one of the core study models, although it is useful to articulate its status in this context as indeed a third, albeit slightly hidden, Bayesian hierarchical model constructed within this study because the claim is obviously both true and relevant to the organizational tropes of this section. However, the fact remains that the implementation of this model was, strictly speaking, non-essential, whereas the previous Models (I) & (II) were essential in the ultimate calculation of species status. Nuances aside, all conventions and features outlined in Model (I) and Model (II) are represented equivalently in Model (III); however, the number of secondary parameters of interest is even fewer still than that of Model (II). Thus, Table 20 is concerned with all relevant Model (III) outputs and may be given by a single table. The content of Table 20 is:

- Marginal posterior estimates of mean natural mortality (M) for (17) species (Table 20), some of which are new to the entire marine science literature, specifically the Longfin Mako (*Isurus paucus*) and possibly the Gulper Shark (*Centrophorus granulosus*);
- Marginal posterior variance *within* samples;

- Total goodness-of-fit statistics (D_{bar}, D_{hat}, DIC, pD) for Model (III) for selected species;
- Credible Intervals [±95%] for all assessed parameters' marginal posterior distributions.

Table 20. Marginal posterior means for *M*, within sample variance parameters, credible intervals, and total model goodness-of-fit measurements for model (III).

	Posterior Mean	Cr. I		Posterior Mean	Cr. I		Model Goodness of Fit Statistics [Deviance Information Criterion (DIC)]			
No	θ_M	2.5%	97.5%	* σ_z^2	2.5%	97.5%	Dbar	Dhat	DIC	pD
1	**0.1451**	0.1283	0.1620	6.50E-04	2.20E-04	1.58E-03	-87.3	-98.45	-76.15	11.15
2	**0.2503**	0.2098	0.2906	3.74E-03	5.15E-04	1.04E-02	-55.26	-66.32	-44.2	11.06
3	**0.1567**	0.1386	0.1748	7.53E-04	2.42E-04	1.85E-03	-84.3	-95.45	-73.14	11.16
4	**0.1903**	0.1544	0.2260	2.93E-03	4.76E-04	8.00E-03	-59.31	-70.44	-48.18	11.13
5	**0.1845**	0.1541	0.2148	2.11E-03	4.16E-04	5.62E-03	-65.04	-76.23	-53.84	11.2
6	**0.0969**	0.0776	0.1161	8.50E-04	2.61E-04	2.11E-03	-81.87	-93.03	-70.71	11.16
7	**0.1907**	0.1521	0.2291	3.40E-03	5.02E-04	9.36E-03	-56.82	-67.89	-45.74	11.08
8	**0.1611**	0.1237	0.1985	3.19E-03	4.85E-04	8.78E-03	-57.96	-69.14	-46.78	11.18
9										
10	**0.1327**	0.1104	0.1549	1.14E-03	3.09E-04	2.88E-03	-76.29	-87.48	-65.1	11.19
11	**0.1383**	0.1203	0.1563	7.42E-04	2.40E-04	1.82E-03	-84.57	-95.73	-73.41	11.16
12	**0.1148**	0.0933	0.1364	1.00E-03	2.85E-04	2.56E-03	-74.56	-85.22	-63.91	10.66
13	**0.1473**	0.1300	0.1646	6.87E-04	2.28E-04	1.67E-03	-86.14	-97.29	-75	11.15
14	**0.1755**	0.1484	0.2025	1.68E-03	3.76E-04	4.41E-03	-69.05	-80.24	-57.86	11.19
15										
16	**0.1805**	0.1599	0.2009	9.62E-04	2.81E-04	2.41E-03	-79.45	-90.62	-68.28	11.17
17	**0.1397**	0.1158	0.1635	1.30E-03	3.33E-04	3.35E-03	-73.69	-84.87	-62.51	11.18
18										
19										
20										
21										
22	**0.2690**	0.2327	0.3053	3.01E-03	4.75E-04	8.24E-03	-58.97	-70.15	-47.78	11.19
23										
24	**0.4694**	0.3876	0.5509	1.52E-02	7.38E-04	4.57E-02	-33.03	-40.41	-25.64	7.38

* The parameter σ_z^2 models variance *within* samples

Details of Section Figures

For all relevant species, for all nodes of vector parameters {F_{msm} F_{lim}, F_{crash}} and M, box plots and density strips were produced. All boxplots produced were of the convention where the box-structure represented inter-quartile range centered around mean posteriors, arms spanning central 95% of the distribution (i.e. ends corresponds to 2.5% and 97.5% quantiles), and plot baseline equaling the global mean of the posterior means of all nodes of the vector parameter. Selected species (*Sphyrna lewini*; *Prionace glauca*; *Carcharhinus falciformis*) with respect to the later figures are given in this chapter (Figures 36[a–d], 37[a–d] & 38[a–d]); all remaining spp. are given in Ancillary Appendix 2. Similarly, constructed figures for selected species' vector parameters, specifically Shark $F_{i,j}^{ShK}$, annual Shark F_{i}^{ShK}, and 5-year global posterior mean for shark F^{ShK} are given for selected species (*C. longimanus*; *S. lewini*; *C. falciformis*; *P. glauca*; *Stegostoma fasciatum* & *G. cuvier*) in Ancillary Appendix 3. Kernel densities (posterior probability density function) for core parameters are derived and shown in coordination with the aforenoted selected species in Ancillary Appendix 3. Pre-model values for catch mechanism parameters are also given here (for other pre-model values, see Tables 8 & 9). Finally, Sustainability Status Assessment Plots (i.e. F vs. F_{mgmt}) portraying final species status designations were produced. Via cartesian position of individual species within this construct, plots show risk space occupied (and therefore status designation accrued) with relation to the F_{msm}, F_{lim}, F_{crash} thresholds for the 17 species fully assessed (Figures 39, 40 & 41). These plots represent the final analytical end-state of the research endeavor. An additional 3-dimensional plot within an added time dimension represents movement across the F_{crash} boundary by year [2010-'14] for selected species (Figure 42).

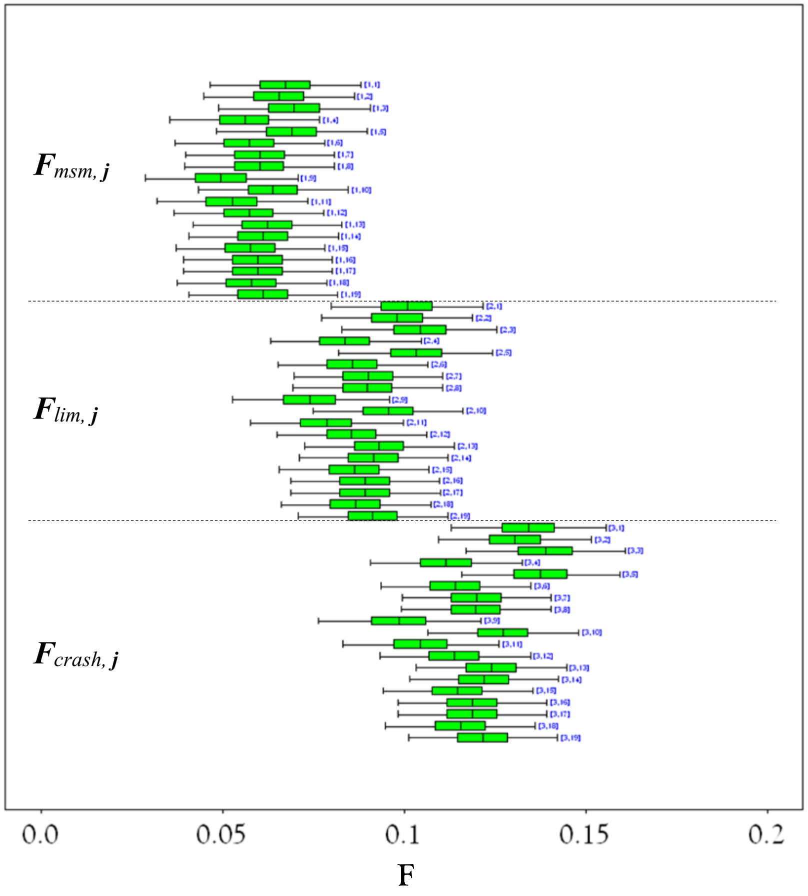


Figure 36a. Posterior means of F_{mgmt} estimators for *S. lewini*.

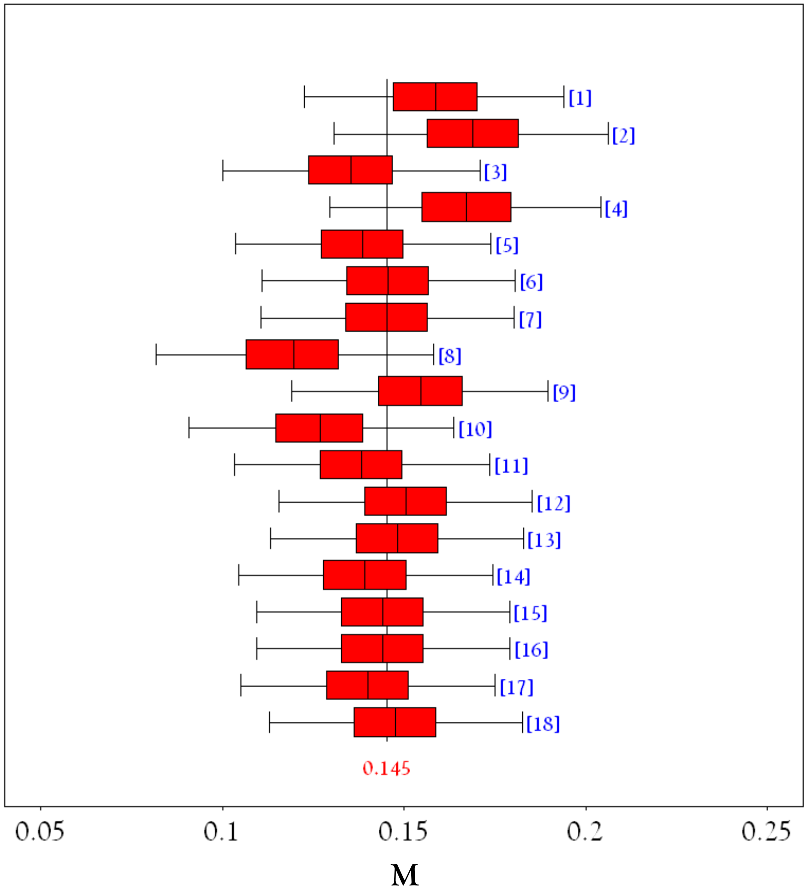


Figure 36b. Posterior means of M estimators for *S. lewini*.

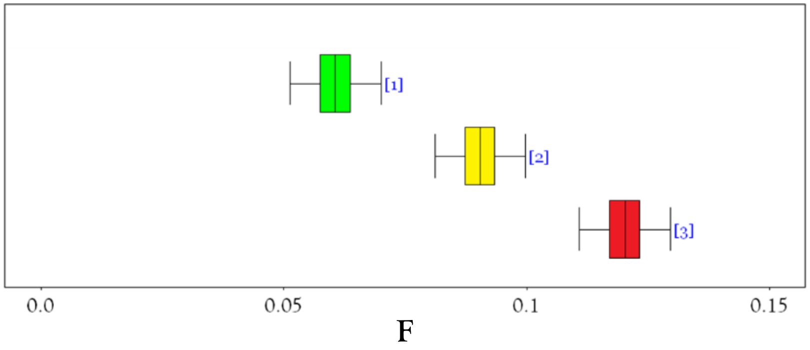


Figure 36c. Posterior distributions of F_{msm} [1], F_{lim} [2], F_{crash} [3] for *S. lewini* (Box Plots).

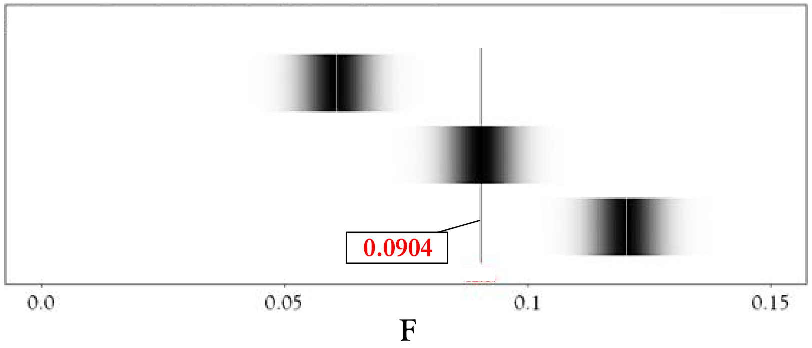


Figure 36d. Posterior distributions of F_{msm} [top], F_{lim} [mid], F_{crash} [bottom] *S. lewini* (Density Strips).

Figure 36[a–d]. *S. lewini* (Scalloped Hammerhead): Posterior distributions of F_{msm}, F_{lim}, F_{crash} & M derived from vital parameters and M Estimators over years (2010-2014) in Indian Oceanic EEZ.

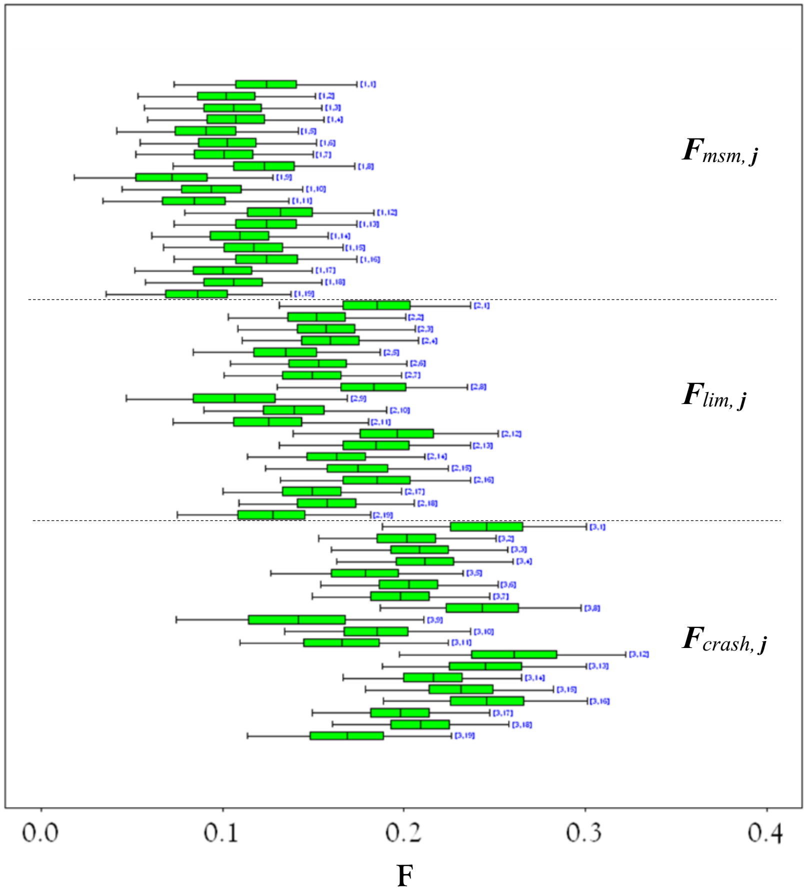


Figure 37a. Posterior means of F_{mgmt} estimators for *P. glauca*.

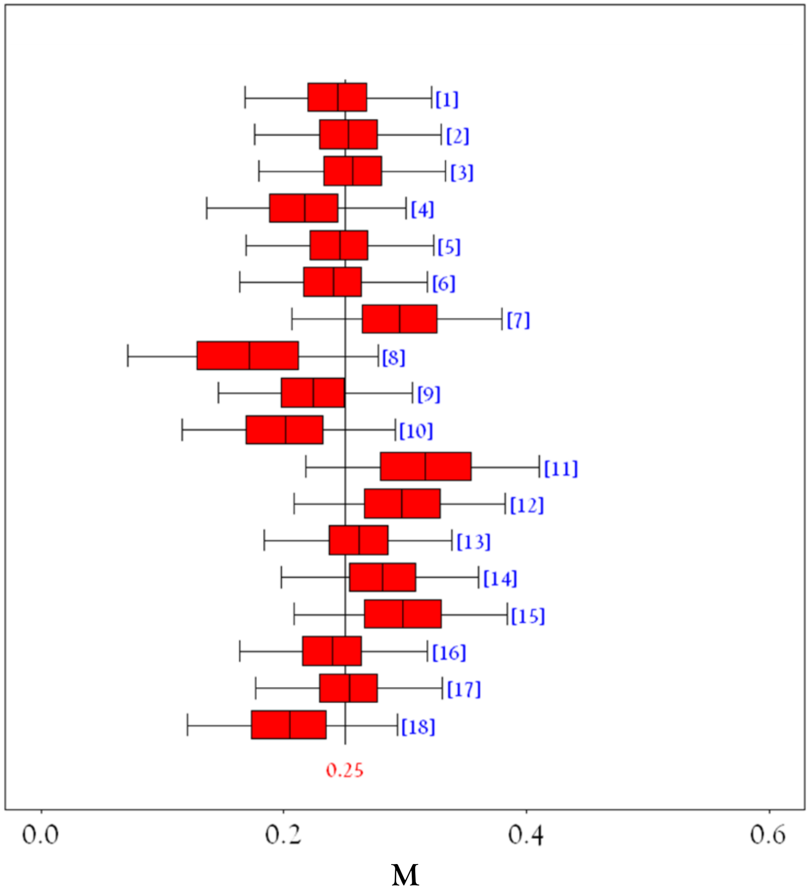


Figure 37b. Posterior means of M estimators for *P. glauca*.

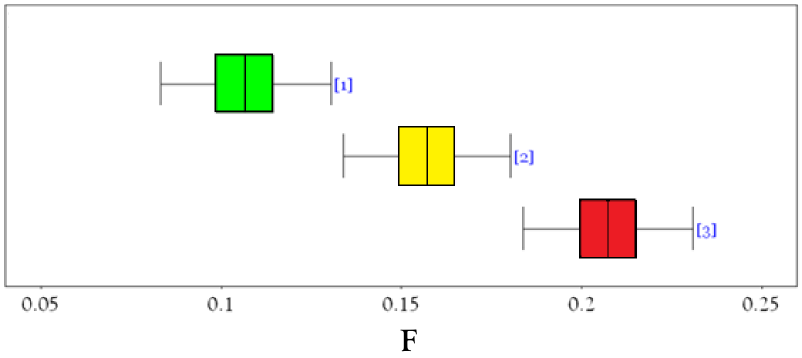


Figure 37c. Posterior distributions of F_{msm} [1], F_{lim} [2], F_{crash} [3] for *P. glauca* (Box Plots).

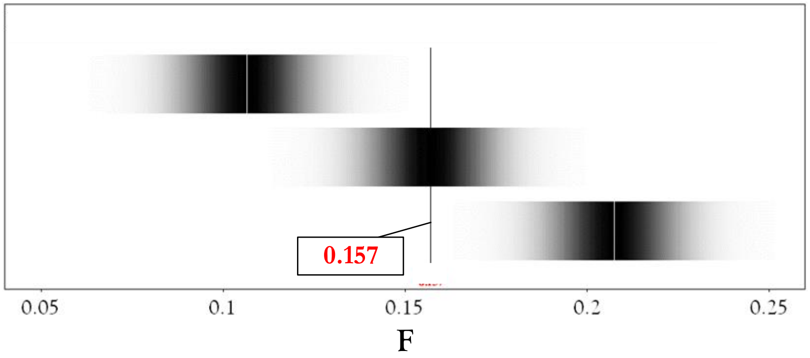


Figure 37d. Posterior distributions of F_{msm} [top], F_{lim} [mid], F_{crash} [bottom] *P. glauca* (Density Strips).

Figure 37[a–d]. *P. glauca* (Blue Shark): Posterior distributions of F_{msm}, F_{lim}, F_{crash} & M derived from vital parameters and M Estimators over years (2010-2014) in Indian Oceanic EEZ.

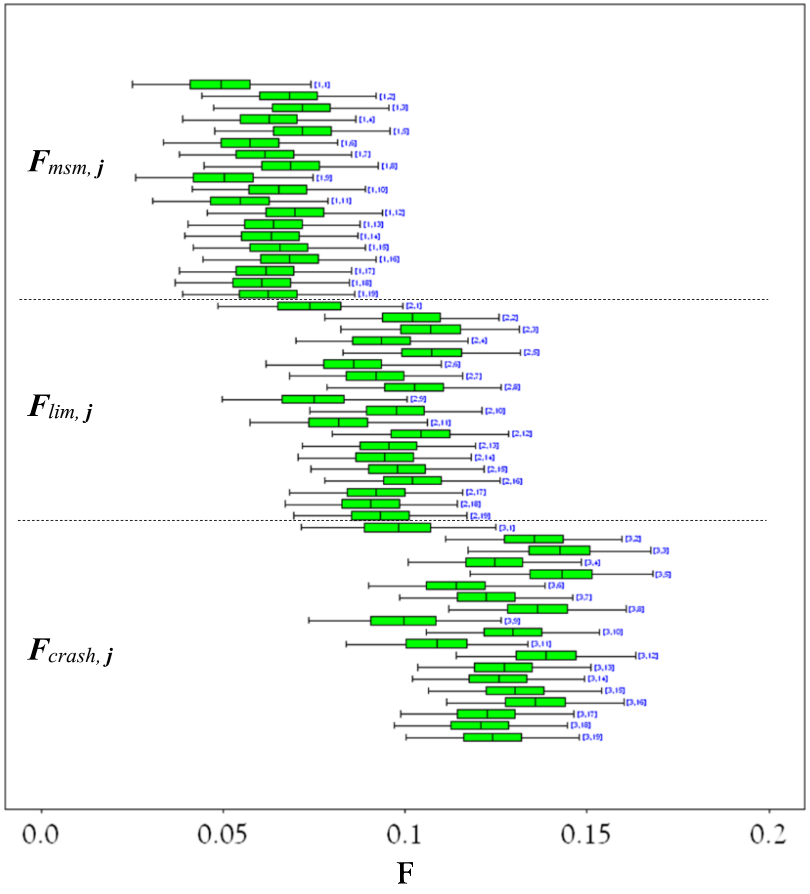


Figure 38a. Posterior means of F_{mgmt} estimators for *C. falciformis*.

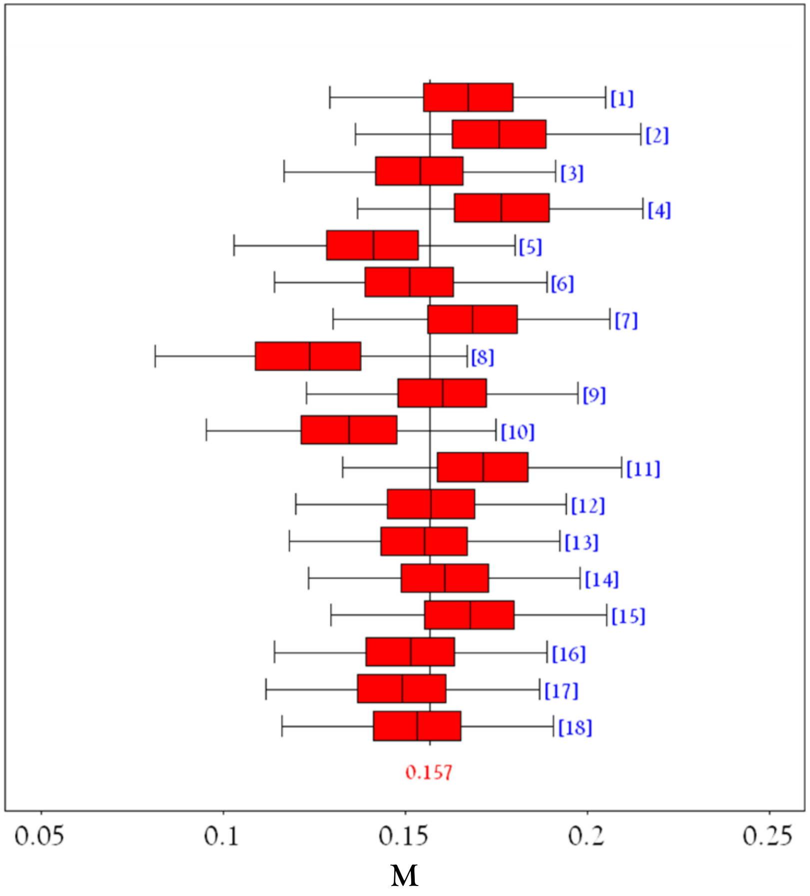


Figure 38b. Posterior means of M estimators for *C. falciformis*.

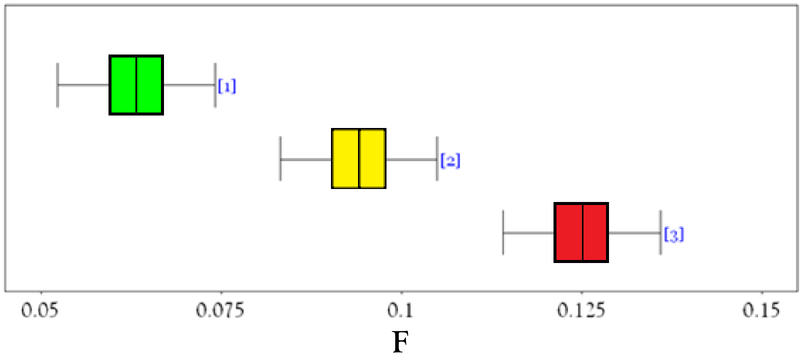


Figure 38c. Posterior distributions of F_{msm} [1], F_{lim} [2], F_{crash} [3] for *C. falciformis* (Box Plots).

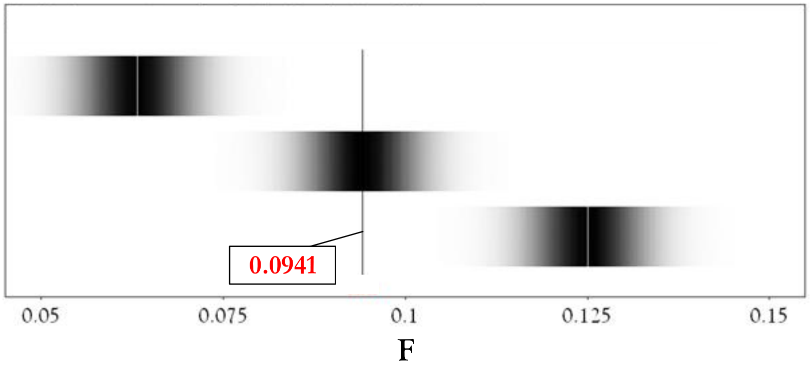


Figure 38d. Posterior distributions of F_{msm} [top], F_{lim} [mid], F_{crash} [bottom] *C. falciformis* (Density Strips).

Figure 38[a–d]. *C. falciformis* (Silky shark): Posterior distributions of F_{msm}, F_{lim}, F_{crash} & M derived from vital parameters and M Estimators over years (2010-2014) in Indian Oceanic EEZ.

Summary Graphical Representations (“The Big Takeaway”): Merging Analytical Streams to Obtain Final Status Designations for 17 Species of Oceanic Sharks in the Indian EEZ

The following F vs. F_{mgmt} figures (Figures 39, 40 & 41) represent the ultimate outcome and analytical end-state of the broader research venture. Newly derived value estimates for fishing morality (F) and corresponding 95% Credible Interval ($C_{R}I$) for 30 species were obtained from the Methods, Part II Bayesian Hierarchical Model (see Figures 23–24) in the form of the marginal posterior of the 5-year interannual grand mean of F (specifically denoted, $\hat{\mu}_{F}^{\omega}$). Additionally, for 17 of the initial 30 species, newly derived values for biologically based F_{mgmt} reference points (i.e., $F_{mgmt} = \{F_{msm}, F_{lim}, F_{crash}\}$) were calculated from the Methods, Part III Bayesian Hierarchical Model (see Figure 34a) as well as corresponding 95% $C_{R}I$. Having been subject to the full program of analyses, these 17 species where thus eligible to receive a final stock status designation.

A following tally of species status was obtained: (1) spp. defined as Low-Risk; (1) sp. defined as Precautionary Medium-Risk species; (3) spp. defined as Precautionary High-Risk; (1) sp. defined as High-risk, (2) spp. defined as Precautionary Extreme-High-Risk; (9) spp. defined as Extreme-High-Risk.

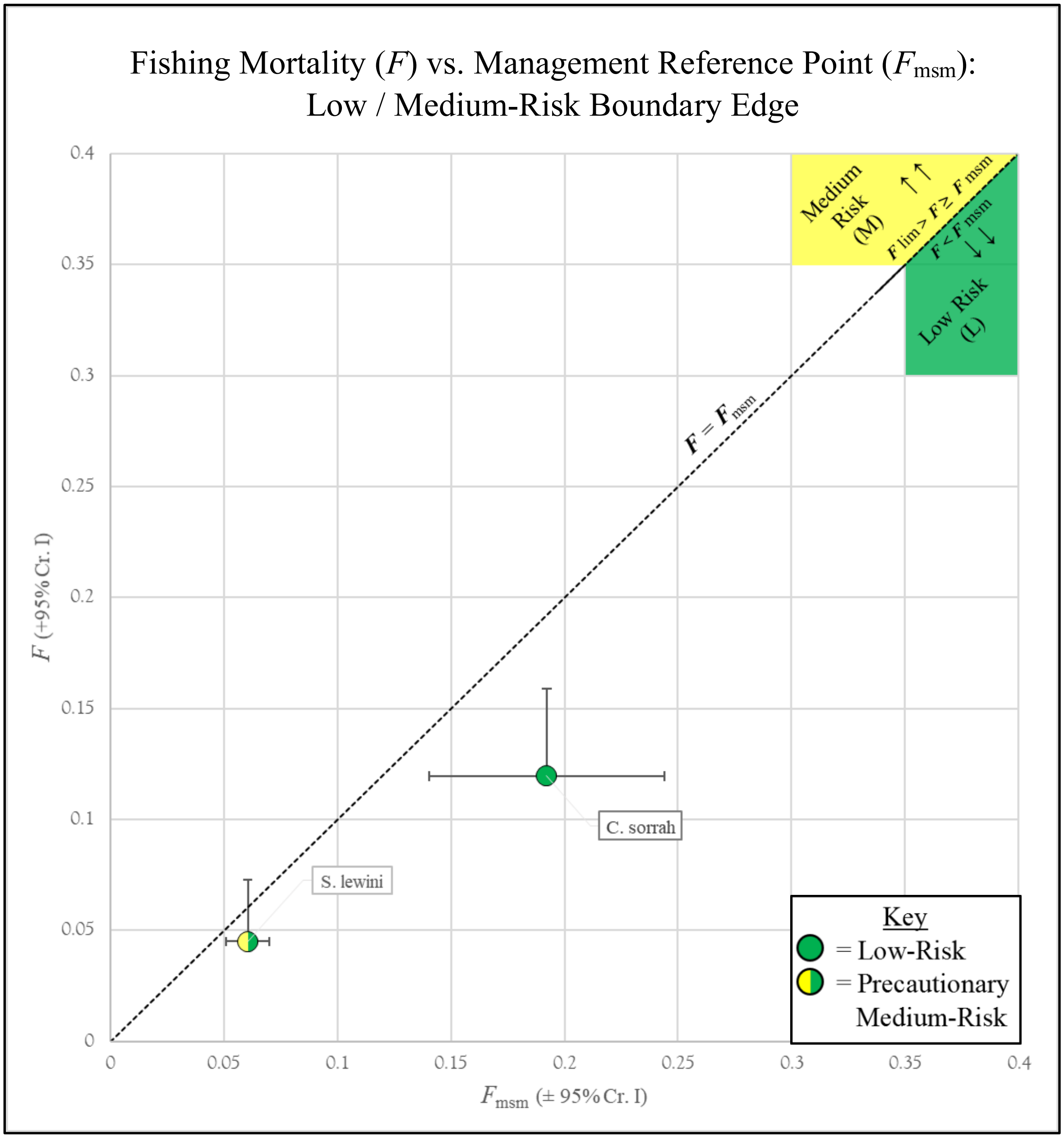


Figure 39. Fishing mortality (F) vs. management reference point (F_{msm}): Low- / Medium-Risk boundary edge.

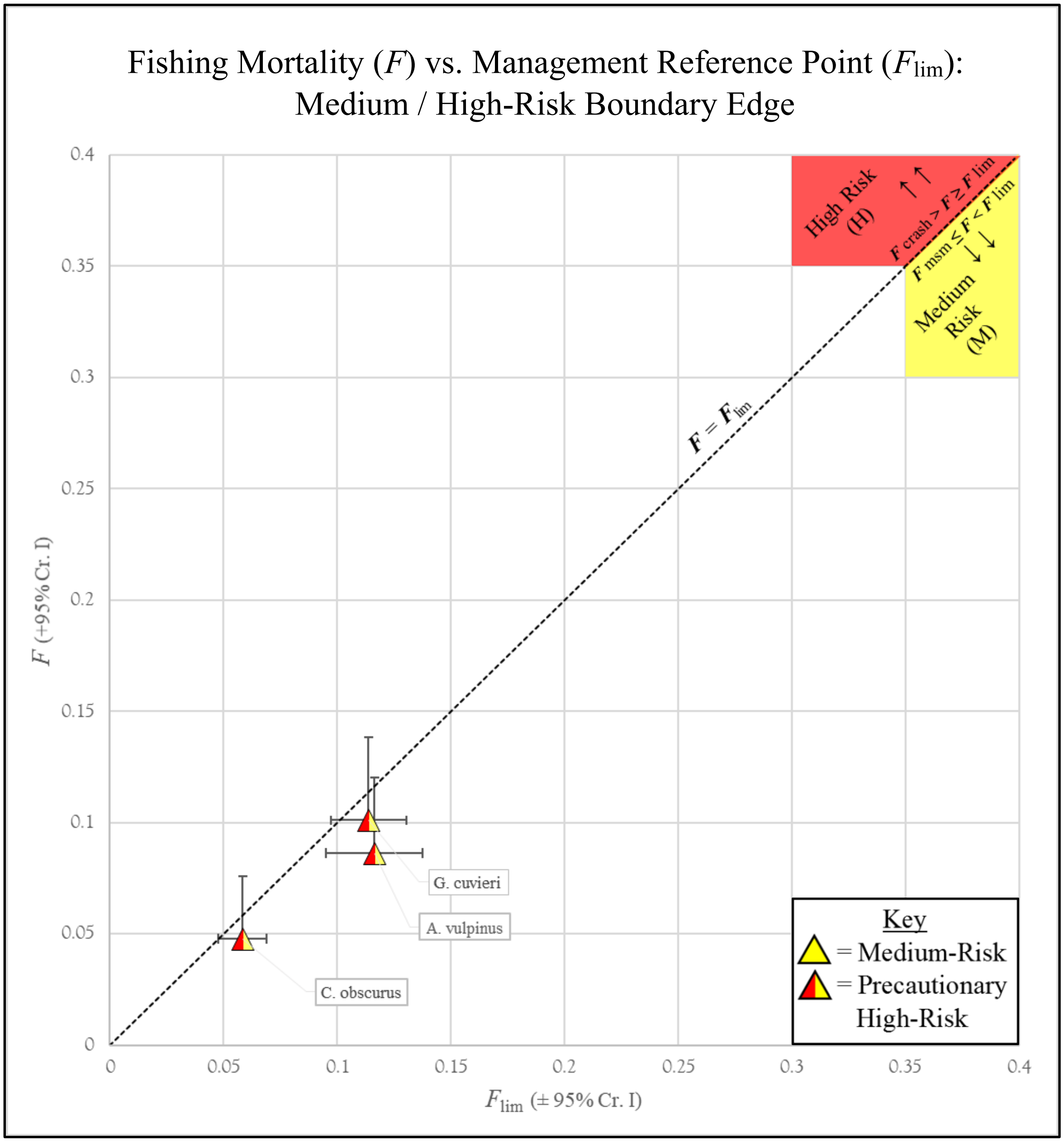


Figure 40. Fishing mortality (F) vs. management reference point (F_{lim}): Medium- / High-Risk boundary edge.

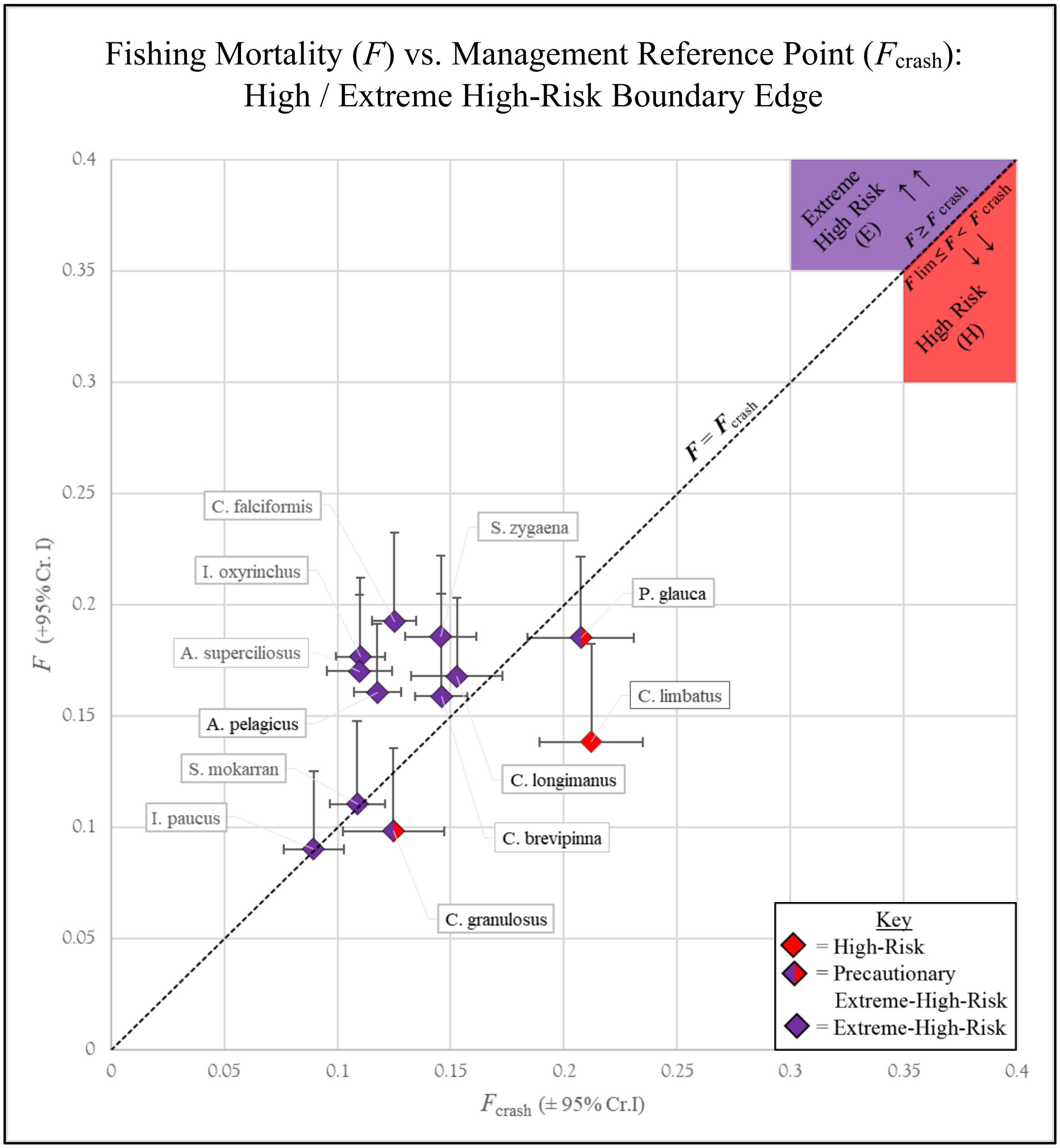


Figure 41. Fishing mortality (F) vs. management reference point (F_{crash}): High- / Extreme High-Risk boundary edge.

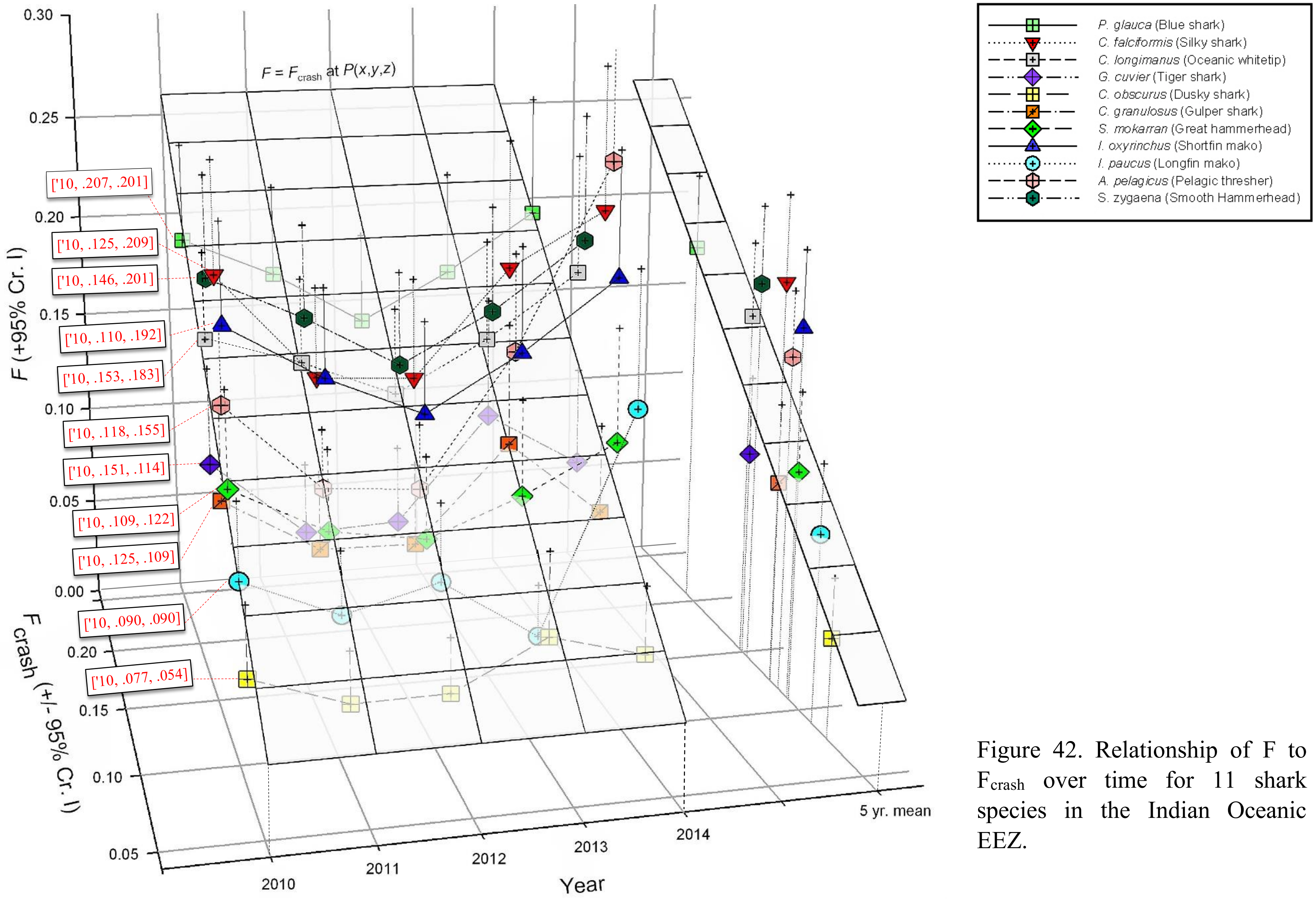


Figure 42. Relationship of F to F_{crash} over time for 11 shark species in the Indian Oceanic EEZ.

Changes in Fishing Pressure over the 5-year Time Period

In addition to the 5-year global mean for F^{ShK} (Table 18a), year-wise estimates were also furnished for individual years 2010-2014 (Table 18b). By graphing this information (Figure 42), a dynamic representation of status rather than simply a point summary is produced. This projection is able to better convey trend movements visually, which are masked with respect to visualizations utilizing total mean values for the time period (such as Figures 39-41).

Stock status over time. Although only a brief snapshot, some important conclusions may be drawn. Only 11 species are given due to the increasing visual confusion accrued with 3-dimensional line graphs. Broadly, species were subjected to increased pressures in 2014 than in 2010, as 8 of 11 spp. had higher values in the former rather than the latter (Figure 42). Furthermore, a dip in fishing effort seemed to occur in the years 2011 & 2012 holistically, with a near resumption of 2010 levels by 2013 and surpassing thereof in 2014. Every species shown penetrates the F_{crash} boundary (which is represented by the translucent plane on the figure) at least once via the F [+95% $C_{R}I$] precautionary threshold (amounting to Precautionary Extreme-High-Risk), even if their total 5-year grand mean was on average less (such as for *G. cuvier*). Extending this inquiry beyond the constraints of the graph proper, a slightly different picture emerges.

Fishing mortality over time. Rough trends in the bycatch mortality regime are shown in Figure 43, where fishing mortality for all 30-species are graphed simultaneously in addition to a trendline, albeit given demonstrably for visualization purposes, and mathematical import should be discounted accordingly. Across the 30 species for which F values were derived (Figure 43; Note—the Pondicherry Shark [*C. hemiodon*] being for the most part omitted from analyses given its status as potentially extinct or extraordinarily cryptic, rending any calculation as pure guesswork and thus designated as "unknown"), 15 spp. had higher F estimates in 2014 than in 2010, meaning that roughly half of the community may be under increasing pressure over this time period whereas the other half have experienced some degree of effort diminishment. In terms of years that amounted to the most prominent mortality pressures, a marked dip in effort is seen over 2011 & 2012 as noted earlier, which is further showcased by the fact that those two years accounted for the highest mortality year for *none* of the evaluated spp. (0 of the 30); otherwise, 2010 was the most intensive year for 7 spp., 2013 was the most intensive for 9 spp., and 2014 was the most intensive for 14 spp.

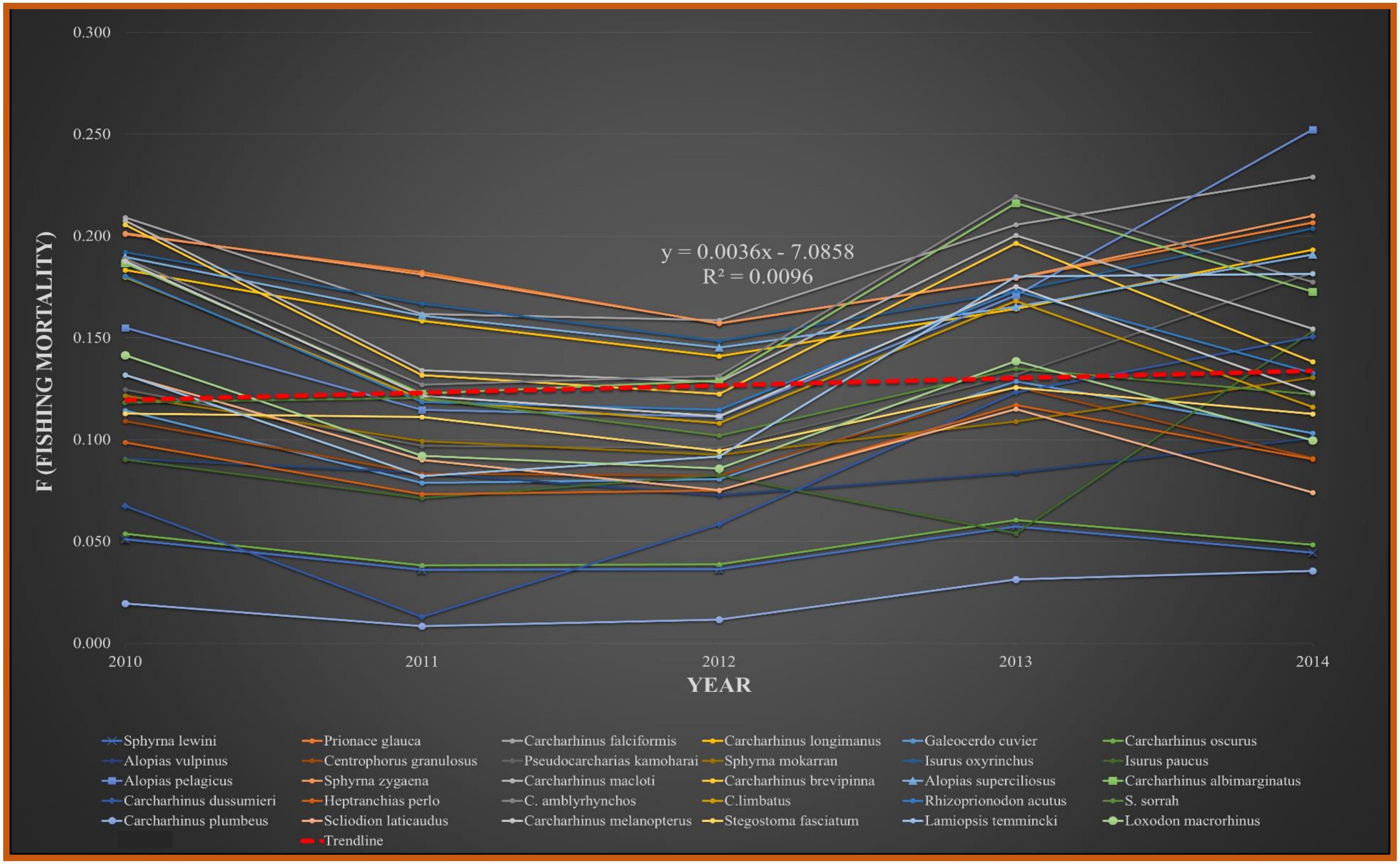


Figure 43. Time series of posterior means of longline bycatch mortality (F) per year for 30 species of oceanic sharks in the Indian EEZ [2010 -'14].

Chapter VI

Discussion

The results of the study lead to a rather clear-cut, but also unexpected interpretation: the community of key oceanic shark species is experiencing significant overfishing under the current paradigm, with the majority of species scrutinized for analysis falling into the categorical range of Extreme High-Risk (53%) and the overwhelming majority above Low-Risk (94%). Thus, my hypothesis is broadly confirmed, but it is certainly not an outcome which should incite much laudatory response. The general status of this outcome becomes quite complex as it seems to problematize the entire domestic maritime strategy of pushing development in the oceanic fishing sectors, especially in search of high value species such as large tunas (James, 2014). The additional scope of honoring existing international conservation agreements to which India is a ratified member state for threatened species (Zacharia et al., 2017) further complicates the prevailing wisdom that the oceanic domain remains an easy solution or release valve in redirecting domestic coastal effort, which is presently well beyond sustainable levels.

Although target species' stocks (such as yellowfin tuna) may be able to handle increased extraction in the oceanic waters around the Indian subcontinent (and Andaman & Nicobar Islands EEZ exclave) with respect to their own long-term sustainability as they are presently under-exploited (Anrose et al., 2013; Sinha et al., 2017, etc.)—a point of view consistently promoted—without a comprehensive shark bycatch mitigation strategy foundationally and fastidiously circumscribed into the designs for future oceanic fishery evolution, and even more so for fishery expansion, ecosystem-scale sustainability is likely unobtainable. It is therefore herein proposed that such a bycatch mitigation strategy in the non-coastal longline fishery be identified as a necessary topical focus in India's forthcoming NPOA-Sharks report and corresponding management framework.

Furthermore, should the results of this study be accepted, given the mathematical end-points linked to Extreme High-Risk stocks, many shark populations will simply be forfeited to regional extinction (extirpation) or relegated to persist at ecologically trivial levels at some time in the medium-term future (less than a generation potentially). The exact timeframe is less well defined, although Worm et al. (2006) postulated perhaps by 2048 for many fished taxa around the globe. Although this timeframe is uncertain, the basic mathematical realities only prescribe one possible outcome, that of population crash for many species. This should essentially be treated as a highly likely end-state should fishery development in this sector proceed according to a "status quo" scenario, and nearly certain in the context of "expansionary status quo" scenario (i.e., the same paradigm as "status quo", but of increasing scale overtime). Only the time frame remains up for debate. The mathematical inevitability of population crash with respect to the specific species stocks in question should be weighed with appropriate gravity against any yield- or goal-based policy strategy for the oceanic fishery that does not mandate proportional actions of mitigation through redesign over time, i.e., a strategy that mandates decreases in shark bycatch mortality in spite of sustained or increased target yield of tuna. Such fishery redesign, should it ultimately be effective, would necessarily be supported by technological innovation (which must actually be implemented both consistently and in a timely manner) and required behavioral changes of stakeholders towards a paradigm of regulation adherence. However, given the inconsistent rate of technological upgrade and sector level technology adoption (mainly due to capital deficiencies seen in the Indian marine fishery holistically, probably largely due to historical inertia of imperial economic subjugation; Bhathal, 2014); the lax data logging efforts in the region (Smale, 2008); and in some circumstances an explicit willingness to effectively game or even conscientiously disobey management regulations outright for the sake of immediate profit motives (especially by the international fleets; Pramod, 2010, 2012; Greenpeace India, 2012), assurances of success may only be at best given with hedged conviction, and they must eschew an additional degree of precautionary consideration to counteract historically shaky performance in these essential components of sustainable design in the region.

Of note, recent changes in the fishing allowances of foreign industrial fleets in the EEZ through the dissolution of the Letter of Permission (LOP) program (F.No. 21002/12/2011-FY(Ind)) in early 2017 seems to be a positive step. If the ban is respected in a significant fashion, it will likely provide an immediate and large reduction in shark bycatch mortality in the sector (for full discussion on LOP developments, see sections: “Letter of Permission (LOP) Program & International Fleet” & “Recent Litigation and Unexpected Termination of the LOP Program in 2017-2018”), which will likely be sustained and act as a de facto stock rebuilding moratorium on the industrial longline fishery while a domestic replacement is mustered and equipped, which is underway (Somvanshi, Varghese, & Varghese, 2008; see also: Five Year Plans X, XI, XII [GOI, 2001, 2006, 2011]). However, judging from past trends, this is by no means a permanent ban (Bhathal, 2014), and international leasing may be revitalized in a different permutation should no domestic enterprise arise to take its place. There is also no guarantee that these fleets will not continue to fish in the extensive oceanic grounds at their discretion, as no concomitant patrolling scheme has been mustered to operationalize this and perpetuate this expulsion.

Furthermore, the production of the “Guidance on National Plan of Action for Sharks in India” (Kizhakudan et al., 2015) signals a recent uptick in national initiative to engage in previous international conservation agreements, specifically The International Plan of Action for the Conservation and Management of Sharks (IPOA Sharks) which was adopted by all FAO parties under the auspices of the FAO Code of Conduct for Responsible Fisheries (the Code) in 1999. Given the slowness of implementation by many party states, a renewed encouragement was given in 2008 by the United Nations General Assembly (UNGA) which encouraged renewed initiative in realizing the IPOA Sharks through the implementation of respective National Plans [of Action] for the Conservation and Management of Sharks (NPOA Sharks) and submission of affiliated documentation. Although a significant increase in development and participation by party states has occurred since then (18 of the 26 highest contributing shark nations have implemented an NPOA Shark) (Fischer, Erikstein, D'Offay, Barone, & Guggisberg, 2012), nearly 20 years later India—the no.2 shark fishing nation—still remains without a formal adaption of an NPOA. However, the 2015 guidance document (i.e., Kizhakudan et al., 2015) which is comprehensive, represents the renewal of the initiative in earnest. As was mentioned earlier however, perhaps only a generation remains between now and final erosion of stock integrity in the region and local extinction, therefore waiting another 20 years is beyond the scope of possible options.

Precautionary Approach

Traditionally and perhaps usefully, the collection of shark species framed within this study comprise some of the most “iconic” oceanic species in the biological community and have garnered critical attention in their own right under international treaty or otherwise. The imperiled state of these stocks as per the findings of this study call for a precautionary sensibility in the management process and thus mirror in kind similar calls by John & Varghese (2009) and Varghese, Tiburtius, Vijayakumaran, Premchand, & Gulati (2011) which call for an immediate precautionary approach to longline fishing in the oceanic region due to high shark mortality and observed declines in catch rates in major exploratory oceanic longline surveys over the broader regional waters of the EEZ.

It is important to note that the F vs. F_{mgmt} status designations generated within this study do not only apply to the threshold of acceptable fishing for the longline fleet alone, but rather for the mortality quota for the entire oceanic stock, regardless of gear. However, it has been shown by this study that the entirety of this quota has likely been overdrawn, and to no trivial degree, by longline fishing alone. This, in and of itself, signals a highly perilous condition, which is somewhat to very surprising, given the lack scope that seems to be acknowledged for the sector. A significant bycatch via drift gillnet has not even been incorporated into this total, hinting that the true scope may even be more intensive.

Oceanic Gillnets Fisheries: A Hidden Leviathan?

In the Indian coastal waters, roughly 35% of tuna are caught using gillnet (Pillai & Satheeshkumar, 2013). Although the same study claims that the oceanic tuna fishery is engaged purely by longline, James (2014) affirmed that large mechanized vessels, OAL 15–18m, are operating gillnets extending to oceanic waters.

A major increase in driftnet catches (a type of gillnet which floats untethered across the surface or usually not far below) has taken place in the Indian Ocean, especially since 1990, despite the moratorium on large high seas driftnets longer than 2.5 kilometers called for by the UNDP in 1992. These very large and increasing catches by Indian Ocean gillnets are totally unique worldwide, because this gear has been very often banned at national and international levels because of its dangerous impact on oceanic ecosystems and sensitive species, such as cetaceans, sea turtles and sharks (Fonteneau, 2011). Regional neighbors Sri Lanka & Iran produced 54% of the total floating mesh driftnet catches in the Indian Ocean over the last 10 years, followed by India, Indonesia and Pakistan.

Large numbers of fishing vessels using gillnets in the Indian Ocean have been identified, such as at least 1000 operating in Iran and greater than 2000 for Sri Lanka. Although these vessels are most often artisanal vessels of small sizes, they are still known to fish very far from their home countries and shores. Additionally, because of their small sizes and artisanal status, at least ostensibly, the total yearly numbers of fishing vessels using driftnets in the Indian Ocean remains questionable. The average length of the Iranian Offshore driftnetter is approximately 22m, with nearly 500 known vessels between 20-30m, hardly qualifying this sector as purely artisanal (Fonteneau, 2011). Furthermore, Fonteneau (2011) calculates that if the legal theoretical length of nets are around 2.0-2.5 km, and two nets are used per vessel; however, there exists few legal controls regarding real, in-the-field lengths of fishing nets by the flag countries, although the IOTC has recently issued a binding resolution on the ban of gillnets or any combination of nets exceeding 2.5km (IOTC Resolution 12/12, taking force in November 2017). The number of vessels is at least 3000 operating throughout the year, so a reasonable estimate as to the length of permanently deployed driftnets, although empirically unknown, is likely between 6000 to 12000 km in the Indian Ocean at any given time (Figure 44).

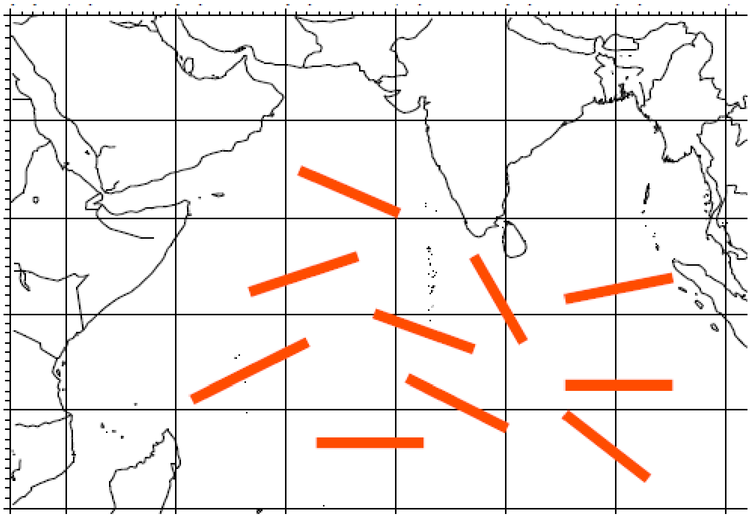


Figure 44. Schematic of combined length of plausible oceanic gillnet operating permanently in the Indian Ocean. Approximate scale-wise conceptual view of the total length of drifting nets that may be deployed daily day a fleet of 3000 vessels using 2.5 km long nets. Reproduced from Fonteneau, A. 2011 [IOTC-2011-WPEB07-INF32].

Therefore, long-line may not be the only vector by which bycatch mortality is being accrued. The degree of oceanic drift gillnet activity common in the region indicates this might also be a substantial source of bycatch mortality. However, express quantification of which remains outstanding (Ardill, Itano, & Gillett, 2013 [SmartFish Report: SF/2013/32]). I refer to oceanic gillnet as the "hidden leviathan," meaning that it is potentially an existential threat, both well-hidden yet lurking on the peripheries of comprehension, as to be a cause of great dread yet uncertainty as well. This analogy was not chosen in passing, and tightly mirrors the situation and hand: that the effort footprint, and thus bycatch mortality contribution, of longline effort alone may not amount to a complete picture of the cumulative fishing effort portfolio within the oceanic region (MARG, 2012 [ISSF Technical Report 2012−05]; Aranda, 2017 [IOTC-2017-WPEB13-18]). Noting that the longline effort alone brings certain species well beyond sustainable mortality levels, the insinuation that a second, and possibly more significant, sectorial gear is being deployed in the form of oceanic driftnet is of utmost alarm. Estimates of impact via the long-line fleet alone sound a credible warning for sharks in India's oceanic waters, as this form of fishing effort in-and-of-itself far outstrips desired sustainability thresholds for many shark stocks, yet it does not even address or incorporate the additional effects of a significant driftnet fleet and its associated mortality pressures. The resulting picture, once completed, will almost certainly depict a situation far more imperiling to the longevity of resident shark stocks than otherwise revealed by this study.

Summary of Calculated Risk Designations for Effected Species and Other Conservation Designations

Many of the species represented across the various SAFE risk categories, but especially those which received higher designations within this study, are also subject to

Table 21. Summary of assessed species SAFE risk designations for Indian Oceanic EEZ and other affiliated designations (ICUN, CITES, and CMS).

Sp. No.	Common Name	Scientific Name	IUCN Status	CITES Monitored	CMS Protected
Low Risk					
24	Spot-tail shark	*Carcharhinus sorrah*	NT	–	–
Precautionary Medium Risk					
1	Scalloped hammerhead	*Sphyrna lewini*	EN	Appx II	Appx II
Medium Risk					
NA					
Precautionary High Risk					
5	Tiger shark	*Galeocerdo cuvier*	NT	–	–
6	Dusky shark	*Carcharhinus obscurus*	VU	–	Appx II
7	Thresher shark	*Alopias vulpinus*	VU	Appx II	Appx II
High Risk					
22	Blacktip shark	*Carcharhinus limbatus*	NT	–	–
Precautionary Extreme High Risk					
2	Blue shark	*Prionace glauca*	NT	–	Appx II
8	Gulper shark	*Centrophorus granulosus*	DD?	–	–
Extreme High Risk					
3	Silky shark	*Carcharhinus falciformis*	VU	Appx II	Appx II
4	Oceanic whitetip	*Carcharhinus longimanus*	VU	Appx II	–
10	Great hammerhead	*Sphyrna mokarran*	EN	Appx II	Appx II
11	Shortfin mako	*Isurus oxyrinchus*	VU	–	Appx II
12	Longfin mako	*Isurus paucus*	VU	–	Appx II
13	Pelagic thresher	*Alopias pelagicus*	VU	Appx II	Appx II
14	Smooth hammerhead	*Sphyrna zygaena*	VU	Appx II	–
16	Spinner shark	*Carcharhinus brevipinna*	NT	–	–
17	Bigeye Thresher	*Alopias superciliosus*	VU	Appx II	Appx II

NT=Near-Threatened; VU=Vulnerable; EN=Endangered; DD=Data Deficient trade controls and general protection under either/both the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Convention on Migratory Species Protection Agreement (CMS). India is a ratified member Party to both conventions and thus is theoretically obliged to respect/implement necessary control actions. Many species represent some of the higher echelon risk categories of the IUCN Red List Designations as well (IUCN, 2017-3). A summary of species status designations and affiliated controls are given in Table 21, as well as restated below:

- Of the (1) Low-Risk species, *C. sorrah* is defined as IUCN Near Threatened (NT).
- Of the (1) Precautionary Medium-Risk species, *S. lewini* is controlled under CITIES (Appx II) and CMS (Appx II) agreements and is defined as IUCN Endangered (EN).
- Of the (3) Precautionary High-Risk species, *A. vulpinus* is controlled under CITIES (Appx II) as well as CMS (Appx II) agreements and is defined as IUCN Vulnerable (VU); *C. obscurus* is controlled under CMS (Appx II) agreements and is defined as IUCN Vulnerable (VU); *G. cuvier* is defined as IUCN Near-Threatened (NT).
- Of the (1) High-Risk Species, *C. limbatus* is defined as IUCN Near-Threatened (NT).
- Of the (2) species determined to be Precautionary Extreme-High-Risk, *P. glauca* is controlled under CMS (Appx II) agreements and is defined as IUCN Near-Threatened (NT). *Centrophorus granulosus* is defined as IUCN Data Deficient (DD).
- Of the (9) spp. defined as Extreme-High-Risk, (6) spp. are controlled under CITIES (Appx II) agreements (viz., *C. falciformis, C. longimanus, S. mokarran, S. zygaena, A. pelagicus, A. superciliosus*) and (6) are controlled under CMS (Appx II) agreements, (viz., *C. falciformis, S. mokarran, I. oxyrinchus, I. paucus, A. pelagicus, A. superciliosus*); (4) spp. are privy to both (viz., *C. falciformis, S. mokarran, A.*

pelagicus, A. superciliosus). *C. brevipinna* is defined as IUCN Near-Threatened (NT), *S. mokarran* is defined as IUCN Endangered (EN), and the remainder are defined as IUCN Vulnerable (VU) (viz., *C. falciformis, C. longimanus, S. zygaena, A. pelagicus, A. superciliosus, I. oxyrinchus, I. paucus*).

Signals and Patterns of Relative Risk among Shark Species

For any particular shark species, the level of realized risk is driven by (or derived from) the calculated, species specific values of two key components, namely 1) biologically based reference points (F_{msm}, F_{lim}, F_{crash}) and 2) bycatch fishing mortality (F). Although realized risk may only properly be determined via the evaluation of the values of the two above components in relation two each other, relative risk (specifically the increase thereof) may be viewed as any condition that decreases the value of biologically based reference points or increases bycatch fishing mortality in a comparison to a second hypothetical species or equivalent population where all other factors are held equal. Inversely, a condition causing the increase of reference points and the decrease of F would result in a decreased relative risk, all things held equal. In this way, specific mechanisms can be singled out for their role in risk modulation individually and independently, and thus some trends and patterns can be identified.

In the case of the former component (i.e., biologically based reference points), vital parameters and their interrelationship provide the mathematical/theoretical basis for output values derived, specific intensities of which either increase or decrease relative risk via the net outcome of their respective combinative contributions within specific applicable equations. Combinations resulting in lower values for the calculated reference points would represent higher relative risk, as the fishing levels needed to realize said reference points would necessarily be lower and easier to obtain, the inverse holding true as well. However, to reiterate, the determination of actual, realized risk can only be furnished when mortality levels are evaluated in context of these reference points, as even if the reference points produced are low, establishing a higher relative risk, if the bycatch mortality is proportionally low as well, there is no increase in realized risk, even with the depressed values of the reference points.

In the case of the latter component (i.e. bycatch mortality), factors which contribute to the final calculated outcomes, and thus relative risk of any given species, are the numerical characteristics of the following features: target species (Yellowfin Tuna) fishing mortality, catchability mechanism variables (Encounterability, Selectivity, and Post-Capture Mortality [q_i^h, q_i^λ, PcM_i]), and finally the proportion of geographic overlap between longline fishing station area and habitat area with the Fishery Jurisdiction Area, specific regions of areal overlap between species habitat and fishing station effort being additionally sensitive to species occurrence probability expressed therein. An increase in the value in any of the above features would signal an increase in the potential for risk, or relative risk.

Numerical sub-drivers of component (1) or management reference points. Although it is difficult to know purely from face value alone how a unique set of species values will play out over the study's total network of equations and relationships—which is obviously the purpose of administering said calculations in the first place—specific intensities of expression of certain vital parameters will, generally speaking, result in higher relative risk. In a hypothetical comparison where all other potential factors between two species are held essentially equal, the species exhibiting a more intense expression of the following vital parameter characteristics would accrue a higher relative risk: larger size at maturity, larger total size, greater age at maturity, slower growth rate (usually linked with longer generation time), and longer lifespan (usually linked with later age at maturity). Although not expressly integrated into study considerations, the following characteristics would also signal a greater comparative potential risk of a species: higher trophic level, lower fecundity, and longer gestation period.

Though likely with many caveats, a general rule is that species with slow growth rates and extended longevity will likely have a higher risk potential (relative risk), and species with fast growth rates and short longevity will have a lower risk potential. More reductively still, larger sharks will likely have a higher risk potential while smaller sharks will have a lower risk potential. A significant exception being a number of deep sea sharks, some of which do not grow very large but do grow extremely slowly; however, to add further nuance, there certainly exist very large deep-sea shark species (such as the Pacific Sleeper shark [*Somniosus pacificus*] and Greenland Shark [*Somniosus microcephalus*] among others).

Numerical sub-drivers of component (2) or bycatch mortality. The value of target species (in this case yellowfin tuna) mortality is an important numerical sub-driver for the final derived value of bycatch mortality (i.e. shark mortality), and thus relative risk. In any real situation, fishing mortality rate for a target species is constant relative to any specific bycatch species under evaluation; therefore, the utilized set of values would not change from one species to another species and thus will not affect one species' relative risk more than another. Said differently, such a case where different values for target species mortality would exist and be used for different species is essentially a non-sensical situation, even if it technically can be produced for the sake of a hypothetical example (i.e., extant only in the form of a thought experiment). Although values of target species mortality may not modify relative risk between species, since it is functionally constant in that respect in any realworld scenario (a single target species mortality exists in a given discrete situation, and species specific bycatch mortalities are pegged to it); however, should the situation change, and take on a different discrete character (say by increased fishing effort), a change in target species mortality may modify relative risk collectively and proportionally across all species simultaneously. The higher the fishing mortality rate for target species, the higher the bycatch mortality rate for bycatch species (abeit the increase incurred proportionally with respect to the species' specific character), and thus higher relative risk.

In relation to catch mechanism variables (q_i^h, q_i^λ PcM_i), these values can have a significant effect on bycatch mortality estimates and thus relative risk. Unlike the former value sub-driver of target fishing mortality, the catch mechanism variables are unique to individual bycatch species. For each of these three variables, the closer they are to a maximum value of one, the higher the estimated bycatch mortality and thus higher relative risk, all other factors being held equal. Predicting which species attain what scores is difficult in precise terms; additionally, direct empirical values are few and are generally specific to a certain fleet and therefore may have limited cross-applicability. However, the following trends were broadly predicted via this study's estimation schemes, which were based largely on theoretical considerations, apart from instances where a value was expressly given in the literature for these variables and thus utilized directly. Verification however would require empirical follow up.

In relation to sharks caught as bycatch by the oceanic LL sector of the Indian EEZ specifically, for encounterability (q_i^h), generally speaking, the shallower the core habitat zone of residence, the higher the relative risk (epipelagic being the highest); risk potential for deeper zones decreased with depth.

For selectivity (q_i^λ), the larger the species the higher relative risk presumed, up to a certain point (400cm) however, after which relative risk decreased again, and inversely the smaller the species the lower potential for risk (when below 400cm). However, increases and decreases in (q_i^λ) values occurred at specific min and max endpoint values of a specified length range (i.e. stepwise), and not continuously (at least in this study's species estimation criteria, which was fairly general). Therefore, unless otherwise given by a specific, empirically derived value taken from the literature, most species exist in the highest risk designation despite varying a reasonable degree in average size. This is due to the fact that the highest-risk length-range was so large (20-400cm) that it effectively encompassed the average sizes of essentially all relevant shark species. So, on a granular scale within a specific size range, and thus relative risk within said range, it would not be possible to say with any certainty whether larger or smaller species would actually have a corresponding larger or smaller value for encounterability, and therefore this trend should be applied cautiously at a total scale and is largely inconclusive among similarly sized species.

Regarding Post-Capture Mortality (PcM_i), no particular predictive patter was readily identified as to why a species may have a higher or lower value; though, higher values accrue higher potential risk, while lower values accrue lower potential risk However, since many species lack specifically published values (and considered unknown), they were simply given the highest risk value for PcM_i as a precautionary measure; though, this treatment of unknown PcM_i values is not unique to this study and has been applied elsewhere (Zhou et al., 2011). Other authors have used empirically derived PcM_i values of sister taxa or otherwise highly allied species to stand in for this unknown where relevant, so potentially there may be some similarities among closely related and morphologically similar species in relation to post-capture morality (Cortés et al., 2010; Cortés et al., 2015).

However, operative hypotheses for predicting PcM_i do exist in the literature. One such hypotheses postulated probable higher PcM_i values for species exhibiting ram-ventilation oxygenation strategies, i.e., species that must keep swimming to oxygenate their gills, rather than having designated musculature that allows for active oxygenation by independently pumping water over gills regardless of total body movement. Such species may incur a much greater risk to experience asphyxiation under a limited mobility situation while on-line or actively hooked. Increased soak-times of gear may exacerbate this situation still further, and as such, hook soak-time may play a part in PcM_i value experienced by these species (Gallagher, Orbesen, Hammerschlag, & Serafy, 2014). In another hypothesis, PcM_i is predicted to garner higher values for species more sensitive to temperature changes, as they may be held at a specific temperature for a certain period of time in relation to the depth of catch, which then may induce high levels of physiological stress should it be unfavorable, possibly to a fatal degree (Gallagher et al., 2014). This brief list is certainly not exhaustive; however, such particular criteria were not aggregated for the species within this study, and as such the linkage of such features to the values of PcMi, when empirically derived, remains unknown for this study's core fishery of interest.

Finally, all things holding equal, species with higher percentage of core habitat overlap with fishing station effort would accrue higher relative risk, and species with higher Occurrence Probability within the area of overlap would accrue a still higher relative risk than those with lower occurrence probabilities but equal areas of overlap. This is due to the fact that an area of habitat party to a specific amount of fishing station area overlap, in which a higher species Occurrence Probability is also present, is worth more to mortality calculations, and thus accrues a greater relative risk, than that of an identically sized area with equal fishing station overlap which however expresses a lower species Occurrence Probability.

Although unevaluated in this study, there may be clustering or correlation of certain intensities among groups of biological traits (Liu et al., 2015), such as habitat preference, proportion of overlapping areas, and relevance of species occurrence probability with said areas. There are, however, enough unique, species specific and idiosyncratic combinations that direct calculation is often more useful than prediction, especially in the context of the final risk calculation as it pertains to this study.

Discrepancies in Conceptualization of True Scale of Oceanic Longline Sector and the Impacts of its Actors

A spectrum of positions exists in the contemporary literature regarding the true extent of the oceanic longline fishing sector and the nature of its constituent actors.

Although a definite consensus exists that the domestic (fleet) contribution has historically been limited, only beginning formative progression towards near-industrial levels both in vessel number and technical capacity since the early 2000’s (Sinha et al., 2017), significant outstanding disagreement remains in relation to other important features, primarily with respect to the contribution and impact of the foreign industrial fleets—which have been in residence in the oceanic waters since the 1980’s onwards. In this regard, claims vary significantly.

On one extreme, certain writers and investigators cite vast bycatch and relatively rampant IUU fishing arising from these legacy fleets which have operated in one guise or another via special promissory schemes in the background of the extensive Indian economic waters and somewhat nefariously for many decades (Greenpeace India, 2012; Hornsby et al., 2015a, 2015b; Pramod, 2010, 2012). The effects of this have led to a significantly greater exploitation level overall and a generally more tempered expectation of the current resource potential of stocks according to such citations. However, on the opposite extreme, other writers and experts posit that the fishery is mostly unexploited and even go as far as claiming that “hardly any organized tuna fishery in India” exists (DAHD&F, 2014 [also known as Meenakumari Report]) and “there is no organized fishery for oceanic tunas” (Pillai & Satheeshkumar, 2013).

However, significant middle ground is occupied, advocating for further utilization of deep-sea resources (NB: the term “deep-sea”, when used to describe sector level fishing in the Indian fisheries policy literature, is utilized frequently as a looser terminological homologue to “oceanic”, or that beyond coastal and approx. 50-100m depth, but more appropriately that which lies beyond normal capacities/targets of the inshore fishery) through careful escalation to ensure a foundation of sustainable managment, though, with limited express concern as to the residual stock impact enacted by potential IUU fishing from the international industrial charter fleets (Abdussamad, 2012; Abdussamad et al., 2012a, 2012b; Anrose et al., 2013; Sinha et al., 2017). However, Vijayakumaran and Varghese (2010) do apply a slight raising factor (of 1.15) to LOP reported tuna catches. Even in the more moderate literature, Sinha et al. (2017) states that "presently tuna fisheries are the one of the important fisheries in India."

Abdussamad et al. (2012a, 2012b) cites the catch of the oceanic Yellowfin tuna fishery as 82,526 tonnes on average for the years of 2006–2010, all of which was furnished by the LOP fleet, with YFT constituting 94.6% of the total tuna landings in the oceanic fishery. Longline and gillnet gear contributed respectively (30.3%) and (51.8%) of oceanic yellowfin tuna. Fleet strength for all tuna targeting craft is estimated by the authors as well, including an estimate of LOP longlining vessels (Table 22).

Additionally, Abdussamad (2012) calculates the total average LOP tuna landings as 87,240 t per year for 2008–2010 (82,744 t was the average contribution of YFT specifically). Overall, the total Indian tuna fishery had experienced a steady increase in landings from 1951 up to 2008 when the total catch peaked. In the oceanic fishery specifically, tuna catch similarly peaked in 2008 at 100,268 (t) (94,851 t of which was YFT) and has thereafter registered a downward trend (at least through 2012; Abdussamad, 2012; Abdussamad et al., 2012a, 2012b).

All things considered, the present research and state of understanding seems to directly conflict with the assessment of the Meenakumari Report (2014) of "hardly any organized tuna fishery in India." The latter juxtaposition, that is—what is clearly demonstrated by a number of sources and experts as a fishery represented by substantial activity and organization vs. a deeply couched sentiment by other writers and policy analysts that a blank slate exists beyond the coastal drop-off due to the lack of any substantial operating fishery—concisely frames the obfuscating double narrative which is extant in the conceptualization of this fishery. This has likely been allowed to survive due to key gaps in relevant data reporting and their affiliated collection schema (Sinha et al., 2017).

Table 22. Fleet strength involved in the targeting of mainly tunas from Indian mainland & island territories.

Vessel category and gear types	Fleet strength (nos.)
Mainland	
Traditional Crafts (Small longlines/troll lines/gillnets)	4,000–4,500
Medium Longliners (Converted Trawlers; [<24 m OAL]) *	812
Large Longliners (Converted Trawlers; [>24 m OAL]) *	48
Mechanized Drift Gillnetters	28
Large Oceanic Longliners (LOP Vessels) **	80–110
Lakshadweep	
Pablo boats (Pole & line/troll line/handline/gillnets)	295
Traditional units (motorized & non-motorized; handline/gillnets)	370
Andaman & Nicobar Islands	
Motorized (Hooks & line/gillnets)	523
Non-motorized (Hooks & line/gillnets)	1334

Note. Gillnets, handlines and small longlines are also very often operated by deep-sea trawlers during different seasons for yellowfin tunas and large pelagic species. Trawlers would not target YFT using their native gear, and thus their contribution constitutes and auxiliary venture. Table recompiled from Abdussamad et al. (2012a, 2012b).

*Longliners operated from different fishing ports along the mainland. They operate in the outer shelf and adjacent oceanic waters and seamounts with fishing duration of 1-3 weeks. In addition to the above gears, they frequently operate other gears, such as troll lines, handlines and gillnets as well, depending on the ground conditions.

**These constitute the LOP vessels, though ostensibly all longliners (potentially a few dedicated purse seiners), they appear to engage in significant amount of gillnetting as well, obtaining apparently as much as 160% YFT catch by gillnet than that by longline, assuming that nearly the entire oceanic fishery is furnished by the LOP fleet (as demonstrated Abdussamad, 2012), and since only 30.3% is from hook and line expressly, such vessels must operate gillnets with great frequency.

Regional Illegal, Unreported and Unregulated (IUU) Fishing

The conceptual basis of this study uses target species mortality plus other features as a relevant proxy for bycatch species mortality. Therefore, accuracy of target catch mortality is key in obtaining valid results. Restated, fishing mortality in our area of interest (or any area for that matter) is directly tied to catch quantity: ipso facto, deriving viable estimates of catch quantity will directly underpin the quality of our result, being that the metric of catch is paramount to the calculation of fishing mortality. This affirmation leads usefully into the discussion of IUU fishing in the region in terms of scope, typologies, and possible conflicting understandings thereof.

Illegal, unreported and unregulated (IUU) fishing may take a variety of forms but its existence broadly conflicts with the goals and effective management of sustainable fisheries. At a structural level, IUU fishing is difficult to estimate and harder still to fully quantify, as the activity itself is designed to be furtive and clandestine, expressly taking place beyond the observational framework and thus actively hidden from calculations. Generally, such forms of fishing skew management estimations away from the true value by both overdrawing from a quota from which their effort was not intended to be party and introducing error into models by further separating estimates from reality, which may in turn lead to improper quota prescriptions downstream.

It has largely been affirmed that there is some degree of IUU fishing happening in the Indian Oceanic EEZ (Anrose et al., 2013; Dhaneesh & Zacharia, 2013; Greenpeace India, 2012; Hausfather, 2004; Hornby et al., 2015a, 2015b; MoEF, 2011; Pramod 2010, 2012; Smale, 2008; Sridhar, Namboothri, Chandi, & Oommen, 2013), the scope of which, however, is a specific point of debate.

Fundamental uncertainty of true scope comes from the lack of observation as to who is actively fishing in the oceanic zone, what they actually catch, and what they choose to report. In this respect, the claims actually vary quite dramatically; fisheries experts who have spent significant professional careers studying this fishery and ocean habitat frequently claim that the fishery is unrealized or bourgeoning (DAHD&F, 2014; James, 2014), while other express significant concerns about the level of unreported fishing happening in the farther territorial reaches of the EEZ. One type or source of unauthorized fishing stems from regional neighbors' fleets fishing beyond their territorial allowance (Anon, 2010; Pramod 2010, 2012) (see Figures 45[a-c]).

Although fishers from the focal three neighboring countries (Bangladesh, Sri Lanka, and Pakistan) have been identified as IUU fishing actors operating within the Indian EEZ, and thus problematic in the conservation context of Indian fisheries (and therefore of interest to this study), it is more than relevant to note that such activity is not unidirectional, and workers of Indian nationality often perform illegal fishing as it pertains to their neighbor states' maritime claims as well. Moreover, the reciprocation of such infractions is cited to be on the order of 2:1—that is, the number of violations of territorial boundaries (measured in terms of law-enforcement interventions) by Indian fisherman of neighbor's states compared to violations incurred by India from neighbors. I generally was able to calculate this ratio by scraping certain values of interest couched within the Pramod (2010) study.

Almost half of referenced infractions carried out by Indian fisherman are attributed specifically to vessels hailing from the state of Tamil Nadu fishing illegally within the national jurisdiction the Sri Lankan EEZ. However, there need not necessarily

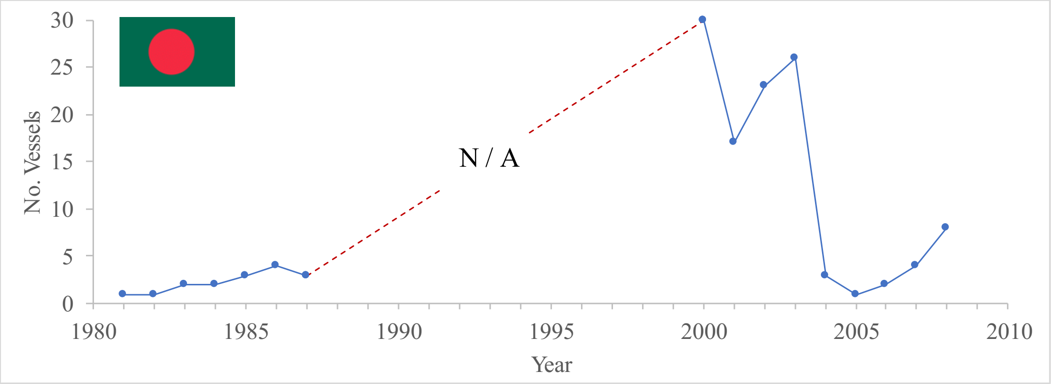


Figure 45a. Number of Bangladeshi fishing vessels detained in Indian EEZ (1981-2008). No data is available for the years 1988-1999. Reconfigured from Pramod, G. (2010).

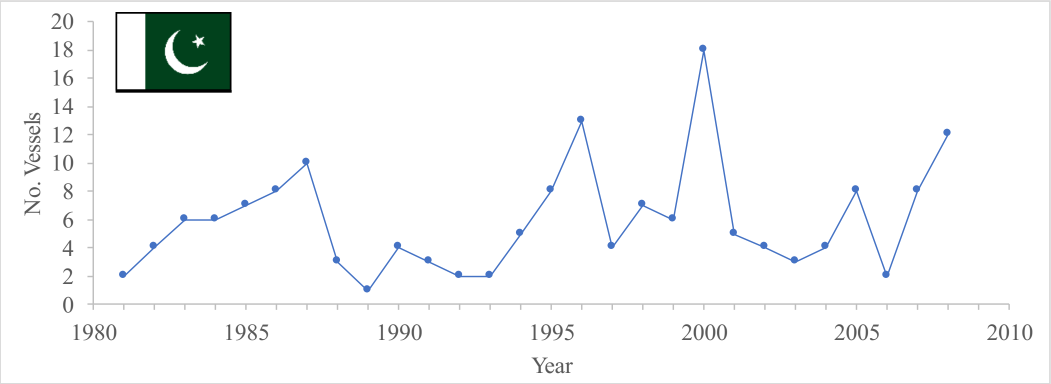


Figure 45b. Number of Pakistani fishing vessels detained in Gujarat (India) for illegal fishing (1981-2008). Reconfigured from Pramod, G. (2010).

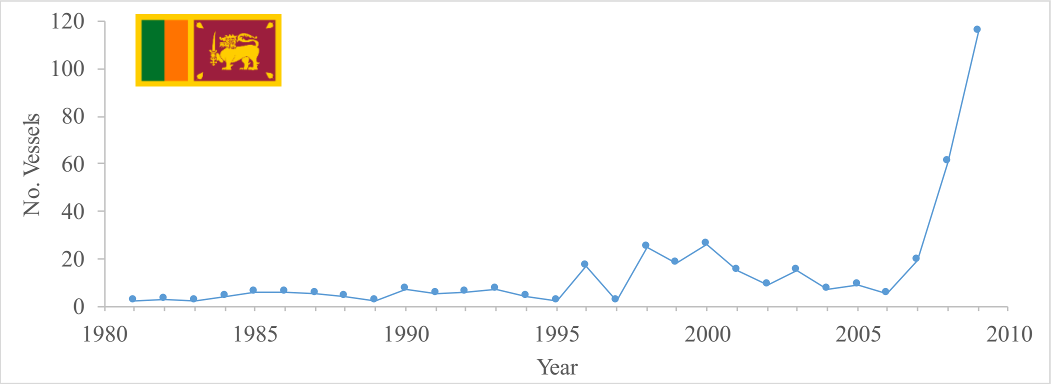


Figure 45c. Number of fishing vessels from Sri Lanka detained in Indian EEZ (1981-2008). Reconfigured from Pramod, G. (2010).

exist any natural relationship between levels of enforcement and levels of real-world infraction by the stakeholders, as at least theoretically speaking, these neighboring countries could essentially just be assuming a comparatively increased defensive and policing-heavy posture towards India, amongst other potential contributing factors as well. Therefore, a metric such as the example furnished by Pramod 2010 (i.e., the number of state-based fishery related incarcerations or enforcement interventions [Figures 45[a-c]), although highly useful, is best considered as a mechanism for actor identification and signal of sectorial recidivism (potentially in the case of Tamil Nadu fleets of India), more so than a determinant of level of impact, at least not before other important factors are also taken into account.

Foreign, vessel-based territorial-trespassing for the express purpose of carrying out controlled or otherwise contextually forbidden economic activities in a clandestine manner (in essence resource poaching), is illegal in a great many ways. However, the phenomenon is experienced with enough relevancy, as shown by Pramod (2010, 2012), that its understanding remains a vital fixture in the comprehension of the entire fishery and especially with respect to the direct IUU portfolio/footprint incurred therein.

If illegal poaching constitutes one important type of IUU contribution within the marine sector in the region generally, a complementary factor of equal importance, though perhaps of more specific import to the oceanic longline fishery of India, is represented in the concern of the scope of IUU practices as they pertain to the promissory schemes allowing certain fleets of international, industrial of vessels to harvest marine resources within the direct territorial claim of India (i.e., the Indian EEZ). Restated, the forthcoming IUU concern specifically relates to practices of the international, industrial vessels/ fleets operating in the oceanic parts of the EEZ under such schemes and their record of participating in IUU fishing activity. These international fleets, although operating legally within the Indian EEZ via resource leasing rights devised by the Indian government (most recently via the LOP scheme and previously via "Joint-Venture" and "charter" schemes respectively), have been frequently cited as operating largely unsatisfactorily and rarely with respect to management prescriptions imposed by the domicile (i.e. India), either through exploitation of elaborate legal technicalities or just via openly and somewhat flagrantly infringing lawful maritime expectations and outright legal requirements, the incentive of which being the financial windfall that may be derived by reaping the maximum extractive potential possible without respect to management limits.

Furthermore, this situation is exacerbated considerably by the "long-leash" given to these international actors by the current arrangement (or Letter of Permission scheme), which grants them privileges not even accessible to domestic fleets (such as transshipment of catch; Mathew, 2003), as well as the nature of industrial fishing technology utilized, which affords such equipped vessels the capacity to essentially never need to interact with the Indian mainland (and thus be privy to at least occasional, passive supervision and assessment) unless they so choose, or at least to a much reduced extent.

Letter of Permission (LOP) Program & International Fleet

As mentioned previously, a major node of IUU fishing concern has been sourced to the somewhat cyclical presence of a non-trivially sized foreign fleet fishing in the Indian EEZ under special leases and often on the fringes of oversight. In its most resent guise (at least before its recall in early 2017; see section "Recent Litigation and

Unexpected Termination of LOP program”), the program which administered fishing allowances to relevant foreign vessels had been known as the Letter of Permission (LOP) program. The history of foreign fishing within the EEZ, and specifically the oceanic region, is related to the following extant conditions: Concisely, back when India first claimed its EEZ (as per the adoption of Territorial Waters, Continental Shelf, Exclusive Economic Zone and other Maritime Zones Act of 1976, and subsequently ratified via the signing of the United Nations Law of the Sea Convention in 1982), knowing that the nation itself did not yet have the capacity to exploit the resources contained within its newly minted EEZ via appropriate fleets and related processing infrastructure, vessels from other nations were allowed to fish within the EEZ under specific leasing arrangements, acting as a form of surrogate fleet which, however, may someday be retired once sufficient domestic capacity had been realized. Thus, the system was born, and ever since (more or less) the introduction of foreign vessels and the allowance of related ventures around that first time—purposed, officially speaking, to both increase domestic technical capacity through knowledge transfer and equipment acquisition as well as act as a functional surrogate for the nonexistent domestic oceanic fishery until such time of sufficient development—the practice has more or less remained active, with equivalent schemes consistently operating in the sector, largely in the background, but not without controversy.

Alleged violations and malpractice by LOP fleet. A laundry list of fairly serious maritime violations has been aired against the operation of such LOP vessels, including the following: “Dual registration, underreporting, illegal transfers of catches, failure to file shipping bills to Indian Customs listing the quantity of catch being taken out while exiting the Indian EEZ, and violation of the Maritime Zones of India Act" (Pramod, 2012; see also: Patnaik, 2008 & Pramod, 2010). Additionally, at-sea finning of sharks by these vessels has been reported via personnel interviews (Pramod, 2012).

Recent reports which specialize on investigation of IUU fishing and reconstructed catch data posit revised claims which range between 2-8 times the officially reported gross tonnage of industrial longline fishing vessels operating in the oceanic sector (Hornsby et al., 2015a, 2015b; Pramod, 2012). Additionally, only about 20% of catch is ever reported, and bycatch is rarely ever reported, according to those same studies, which engaged comprehensive interviews with former joint-venture long-liner employees (Hornsby et al., 2015a, 2015b; Pramod 2012). Bycatch itself likely constitutes at least 50% of total catch for each haul of these vessels (Pramod, 2012). Of the 50–60 industrial LL vessels claimed by the relevant fishing/economic authority of India, only a handful are registered with the IOTC (Greenpeace India, 2012), and the full number remains largely an educated guess, which seems to be underreported by involved registration bodies.

Accusations of illegal transshipment have been made as well as proven by the Indian Coast Guard (on numerous occasions); however, the true scale of actual fishing performed by the LOP fleet expressed in quantitative terms, on the other hand, has been difficult to assess (though, best estimates have likely ben gathered by Abdussamad et al. (2012a, 2012b), which were given previously in the section: "Regional IUU Fishing"), and thus knowledge of true impact remains to a large degree unknown. Since many LOP vessels fishing in these oceanic waters are operating at such great distances from shore, barriers to real-time oversight and enforcement capacity for compulsory practices are encountered de facto by matter of physical distance (at least 6 weeks without resupply for LOP vessels 24–40m OAL [Pramod, 2012]). More generally, the power to observe the system or the actions of its constituents is largely absent, thus rendering the capacity to change or challenge undesirable actions not readily possible.

One family of sources (Pramod, 2010, 2012) makes an economic case for the underreporting of the sector. By establishing the economic break-even costs (or baseline solvency requirements) for sustaining a longline vessel in the regions (in terms of regional points of reference: Pakistan, Thailand, Sri Lankan, etc.), Pramod (2010, 2012) states there is quite a discrepancy in their earnings based on reported catch and the theoretical minimum catch necessary to retain a solvent vessel, and therefore a significant amount of IUU fishing must be occurring by such vessels, as reported catch would not even be close to what is needed to retain base-line solvency of the fishing venture. In addition to citations of illegal transshipping—that is, landing ones catch at mid-sea processing ships and dumping logs afterwards (effectively acting as a catch quota multiplier)—the practice of "Flag hopping," or dual or ambiguous registration of a vessel; many times with willing facilitators within the bureaucratic arms of respective national compliance agencies, has also been notice frequently in such LOP vessels (Greenpeace India, 2012; Pramod 2010, 2012). The ability to flag hop is furnished by the practice of maintaining dual, concurrent registrations in multiple countries, which is illegal, but obviously is an extremely useful tool in the execution of a variety of nefarious fishing activities.

In a recent report by the FSI to the IOTC, potential inconsistences of shark catch in general by LOP long-liners was signaled in an annual report to the Working Party on Tropical Tunas (WPTT) of the IOTC in 2015, where the reported catch/bycatch of sharks by this category of oceanic longliners in India was reported as "0" for the year 2014 (IOTC–2015–SC18–NR09[E]); the dubiousness of this amount is also noted in the meeting notes; though, a resolution of the matter is unknown.

Recent Litigation and Unexpected Termination of the LOP Program in 2017-2018

Significant changes to the status of the LOP program in India broke contemporaneously with the drafting of this manuscript and occurred as the climax of unfolding legal action made in the form of a private petition [WP(C).No. 28818 of 2016 (S)] to the High Court of Kerala requesting judiciary intervention as to the continued allowance of the program (*M.K. Salim v. Union of India*, 2017). Essentially, an advocate plaintiff, M.K. Salim, petitioned the High Court to order the Ministry of Agriculture (MoA), Department of Animal Husbandry & Fisheries (DAH&F) to abandon the continued facilitation of the LOP program, the latter being obliged as a subordinate governmental organ to cease empowered activity should the manner of its execution be deemed unlawful or negligent by the judiciary. The Central Government, vis-à-vis Entry 57, List I, Seventh Schedule of the Constitution of India, has exclusive power to create laws with respect to "fishing and fisheries beyond territorial waters"; the DAH&F, being a direct, specialized extension of the Central Government, is thus empowered to administer such laws. Furthermore, the territorial Water, Continental Shelf, Exclusive Economic Zone and Other Maritime Zones Act, 1976, bars foreign persons or enterprise nearly unconditionally from operating within the area of its EEZ except through express permission of the Central Government, who maintains final territorial sovereignty and discretion on use of the national commons; the DAH&F is therefore empowered to grant such allowances at-will and expressly since it is a federal department. Under the privileges just outlined, it was possible for the DAH&F to permit the fishing of foreign vessels under the Letter of Permission Program. However, the plaintiff contests that the alleged gross mismanagement and inability to adequately control or monitor the LOP program has created a negligent situation of significant detriment to the public interest and is therefore moved to seek final recourse through an appeal to judicial mandamus.

At the level of public opinion, the LOP program had been garnering particular and steadily increasing criticism since its initiation in 2002, which was itself more or less just a cosmetic relaunch of an even more hotly disliked foreign vessel Joint-Venture program, which had to be momentarily retired in 1997, if more in name than spirit, due to immense pressure from the National Fishworkers Forum (NFF). The NFF is an advocacy group (still active in 2018) tasked with the representation of community-level concerns pertinent to the small-scale domestic fisherman in India, who, with respect to the foreign vessel activity, were conceivably being negatively impacted with little tangible benefit; where the two fleets have overlapping interests and fishing grounds, domestic ventures were out-classed and unable to compete with modernized, industrial-strength foreign outfits while additionally receiving little in the form of skill- and capacity-transfer as promised under the initial goals of the LOP directive. Although initial concessions were made in 1997, the reinvention of the former Joint-Venture plan through the LOP program in 2002 demonstrated that a great many policy makers were fully wed to the idea.

The logic underpinning this perennial policy strategy is more or less expressed as the following: Seemingly, allowing a resource base (oceanic fisheries) to lay fallow indefinitely when, alternatively, some marginal gain could be furnished through resource extraction leasing to sufficiently equipped international outfits during the lead-up time to fully-realized domestic capacity (someday), remained attractive and is likely the reason the present LOP and previous related schema remained in place for so long despite a substantial legacy of critical counter-opinion. However, the increasing boldness exhibited in the exploitation of regulatory loopholes by international vessels given the minimum oversight environment and outright rule-breaking by the sector would become too lopsided to adequately write-off as ignorable or otherwise "flawed-but-heirloom" policy for much longer. In one guise or another, the system allowing international fishing had persisted for over 30 years with no tangible development or capacity goals met with the added tinge of greatly frustrating laborer dignity since the decision maker class seemingly did not even have the appetite to enforce rent payment on the valuable commodity that the economically depressed fishing communities aspire to someday inherit. A. Hamid sums up the inherent frustration and fundamental questions as to the logic of the LOP program in an article in *The Hindu* (3 May 2012):

> According to vessel owners interviewed by [*The Hindu*], on average, a vessel nets about 200-250 tonnes of tuna every season. The Ministry's latest records say that currently, 79 vessels are operational in Indian waters under the scheme of which 56 are tuna longliners and the remaining mid-water pelagic trawlers. Yellow fin tuna, which is the prize these vessels are after, sells at $10-15 (Rs.500 approximately) per kg in the international market. By a conservative estimate, from the tuna long liners alone, the catch would be worth Rs.630 crore [~$100 million USD] every season. If this money were accruing to Indian fishermen, there is no evidence to show for it. Nor is it clear how much the export of tuna benefits the Indian exchequer, as there are no public records of the amount paid as export duties. All that is known is that the government of India earned a grand sum of around Rs.8,00,000 [~$11,500 USD] (which is not an annual but a one-time licensing fee).

> Since the scheme seems to have failed on every count, the logical questions that come to mind are who exactly is benefitting from the scheme? Are there vested interests? And despite these breaches and a Central Bureau of Investigation (CBI) inquiry that was initiated into the scheme in 2005, why has no action been taken so far?

By early 2017, the DAH&F had apparently seen the writing on the wall, and with litigation still pending in the form of *M.K. Salim v. Union of India* (2017), on Jan 30th the Department decided to preempt an official decision and ultimately dissolve the LOP programme in the Indian EEZ by its own, independent accord (F.No. 21002/12/2011-FY(Ind) [dated 1/30/2017]). Specifically, the most recent policy renewal of the LOP program and its varied collection of guidelines outlining the stipulations for registration and participation, which was instituted in 2014 (F.No. 21002/12/2011-FY(Ind) [dated 11/4/2014,]), were rescinded in all forms by the aforenoted Order of 1/30/2017. Thus, the legality of LOP fishing was abolished. According to a report in the *Times of India* the "Indian Coast Guard has informed the Kerala High Court that central government has withdrawn its 2014 decision that allowed foreign deep sea [*sic*] trawlers to operate in Exclusive Economic Zone (EEZ) of the country [as of May 2017]" in kind (Haneefi, 6 Mar 2017).

Although a major grievance was already conceded to the petitioner and his cause through the order to terminate the program in late January by the DAH&F itself before the court had handed down an official decision, other demands aired by the petitioner were eventually won in the final judgment of this case (*M.K. Salim v. Union of India*, 2017). Overall the presiding judges, the Hon'bles A.M Saffique and A. Sivarman, were significantly underwhelmed with the arguments of the MoA, DAH&F as to the legitimacy of this LOP programme and produced a rather scathing judgment, a key excerpt thereof, which also cites specific findings from the Greenpeace India report *License to Loot* (2012), is presented below:

> Dr. P. Paul Pandian on behalf of Government of India, who is the Fishery Development Commissioner, Ministry of Agriculture and Farmers Welfare, Department of Animal Husbandry, Dairying and Fisheries, it is stated that the LOP vessels during 2005 to 2015 was having an average annual catch of 316 tons per year. It is also indicated that as against the permissible fleet size of 1188 vessels, not even 10% vessels were authorized through LOP. The Government of India is completely unaware of the total number of LOPs issued in the matter. Further, it is stated that the vessels that had operated in the Indian EEZ range from 18 to 23 [meters] and that too during the tuna fishing season. In other words, there is no clear data available with Government of India regarding the number of LOPs issued, who were operating, the nature of catch, the quantum of catch, the quantum of transshipment etc. The contention that only 316 tonnes per year had been caught by about 18 to 23 vessels is totally unbelievable. On what basis this data was obtained is indicated in a letter dated 2/3/2017 sent by the Fishery Survey of India to the Secretary to Government of India wherein catches are mentioned for each year. Taking into account all the factual circumstances, this figure cannot be accepted. It is totally unbelievable that such vessels will be operated for about 10 years for catching only 316 tons of fish. In the absence of any other data, it can only be assumed that the figures now shown has absolutely nothing to do with the actual catch…But in a case where the Government of India itself was doubtful about the LOP Scheme and its operation and several Committees were constituted for the purpose of ascertaining the functioning of LOP licensees and the manner in which it is being conducted, necessarily it has to be believed that the petitioner has ventilated a valid grievance…
>
> The Meena Kumari report observed that the fleet plan for EEZ allowed operation of 725 vessels comprising 500 pole and line vessel, 110 tuna long liners, 72 Pelagic/mid water trawlers, 18 purse seiners, 15 squid jiggers and 10 trap/hook & line vessels. The subcommittee further noticed that, as on 31/10/2011, there were only 81 valid LoPs of which 74 vessels were either tuna longliners or mid-trawlers. It is therefore rather clear that no proper investigation was conducted into the matter at any point of time. Ext.P8 is the report of Greenpeace. According to the report, problems arise on account of illegal, unreported and unregulated fishing, double flagging in a number of vessels in India under the LoP Scheme, lack of proper monitoring control and surveillance, transshipment loopholes etc. Further, they have also narrated the social impacts caused on account of such unregulated and unmonitored procedures and the economic loss that is being suffered by the Government While concluding, it is stated as under:
>
>> "It is evident that the LoP scheme has yielded very little in the way of tangible benefits, either in terms of revenue, employment generation or the actual development of an indigenous deep-sea fishing industry which might also enable a reduction on fishing pressure in near shore waters. Current

> management efforts are not sufficient, and the limited measures in place are clearly ineffective. As illustrated through this report, the LoP scheme has numerous loopholes and shortcomings and facilitates regular non-reporting or under-reporting of catch and value transshipment of catch in the high-seas, failure to file bills to the Indian Customs listing the quantity of catch being taken out while exiting Indian EEZ, and violations of the Maritime Zones of India Act.
>
> The LoP scheme critically undermines fisheries management in 3 significant ways:
>
> 1. The addition of these industrial vessels under the LoP scheme increases fishing capacity in the Indian EEZ, in a context where there is not enough knowledge about the status of the targeted stocks or what could be considered sustainable yields. This has the strong potential to result in overfishing further out in the EEZ and undermine the future of the Indian fishing industry.
> 2. The LoP has certainly not added any significant value in terms of local employment, income and food security, supporting sustainable livelihoods, while causing a further deterioration of fish population levels and local marine ecosystems.
> 3. Creating a problem in determining actual fishing efforts occurring in the Indian EEZ. While there may be scope to increase fisheries in the Indian EEZ, fleet expansion needs to be carefully planned to avoid over-exploitation. There is an urgent need to put in place adequate management measures for fishery resources in the EEZ, before any further expansion of fishing capacity and increase in fishing pressure in the EEZ takes place. Furthermore, it is important that the development of indigenous fleets avoid destructive fishing practices such as bottom- trawling and large scale long-lining in the EEZ. It is also in India's interest as a progressive voice to demonstrate that it has an effective management system in place, consistent with its obligations under UNCLOS, UNFSA and other international legal instruments. In moving forward, these serious loopholes need to be closed and steps need to be taken urgently towards developing a sustainable and equitable approach to fisheries which does not compromise on ecological imperatives [Greenpeace India, 2012]."

In light of the body of evidence presented over the course of the trial, the following two directions were ultimately issued by within the judgment of the High Court to be carried out by the MOA, DHB&F:

> (i) The 2nd respondent shall constitute a competent Committee to conduct an enquiry into the loss suffered by Government of India on account of the misapplication or non-implementation or lack of procedural formalities in implementing the LoP Scheme and a report shall be obtained within a period of six

> months, which shall be published in the website of the Ministry and appropriate action shall be taken based on the said report.
> (ii) While framing new scheme, Government of India shall also consider the said report and ensure that there is a proper accounting system for the sea wealth that is being caught from the EEZ and proper mechanism to monitor the same. This writ petition is disposed of as above.

Reflections on Methodology

The following section outlines some valid critiques of methodology I have noted. On the whole, data sources chosen as well as methodologies implemented represent the best possible options available or otherwise known to the author, although they are perhaps not equivalent to common best practice. Striving for these standards was intended; however, unavoidable realities made it necessary to pivot to other options, not by choice or ease of execution, but because of necessary circumstances at play.

$A_{i,f}$ Calculation

Perhaps the most notable data-dependent, situational work-around was encountered in relation to the calculation of fishing impact area ($A_{i,f}$). This was ultimately accomplished via somewhat non-traditional means, namely, extraction of grid-based location data of longline fishing station sites from a graphical representation of the Indian Seas featuring those sites (i.e., from published maps by the FSI, without any relevant metadata regarding features portrayed therein, by geometrically estimating and assigning coordinate locations to station sites using the inherent cartographic logic of the representation). In a situation where all options were readily available, the best conceivable practice would have been without hesitation to locate tables of numerical values (metadata) for the fishing station's data points, information held by the Fisheries

Survey of India. However, given that this data is essentially protected from lay access, it was imperative to seek new ways to glean such data. The method employed in this study was such an alternative strategy of necessity, though still deemed to be largely accurate.

Additional Target Species Viable for Inclusion in ρ Estimate

Skipjack Tuna (*Katsuwonus pelamis*) is widely considered the second most relevant ("No. 2") target species within the oceanic longline fishery of the Indian Oceanic EEZ. Although reports vary as to total extent of catch in the region, integrating this species as a secondary contributor to the value of ρ could modify final assessments of bycatch mortality in sharks. However, reports that Skipjack catch is actually only perhaps 5% that of YFT for the oceanic LL sector (Abdussamad et al., 2012a, 2012b) lend a significant credible rationale in the view of the author in support of the decision to ultimately omit this species' profile from integration into the assessment, as it perhaps may have simply acted as a nuisance calculation and perhaps overexpressed its role given that it would have received equal mathematical weight to that of YFT due to the tenants of the Zhou et al. LL equation (which simply takes the arithmetic mean of the ρ of each target species included to derive a final ρ), even in light of its likely depressed catch profile; though, further exploration of the topic is certainly warranted.

Study Concentration on Sharks (Selechii)

In general, the express focus on true sharks (Selechii) as opposed to Elasmobranchii (sharks, rays, skate, sawfish) more inclusively was done as an attempt to concentrate focus and limit potential procedural externalities, but on total reflection of the research effort, there appears no obvious, tantamount reason certain oceanic, pelagic rays need be excluded from this analysis. Certain regional mobulid rays and pelagic stingrays could easily be incorporated into the study pipeline and provide a relevant vector for continued study and direct application of the methods derived for this research.

Although prospective, fishery-scale interaction of mobulid rays with longline gear is suspected to be less prominent than with their Selechii relatives, given different feeding strategies and prey targets driven by distinctive group morphotypes, it is obvious that very large oceanic rays, including giant manta rays (*Manta birostris*) are being brought into market, as can be seen in the photograph taken by the author in Kasimedu Fishing Harbor in Chennai, Tamil Nadu in the Fall 2016 (Figure 46). Although this situation was most likely just a case of not wasting incidental bycatch, the presence of an active market for oceanic manta rays is of considerable concern in a number of respects. *Manta birostris*, or the Giant Oceanic Manta Ray, is presently listed under Appendix I and Appendix II of CMS, Appendix II of CITES, and is presently listed as Vulnerable (VU) by IUCN (Ver. 2019-1).

CPUE & Hook Count Data Availability

One of the hallmark components of this study's methodological approach is that it was able to be analytically functional even without utilizing many more obvious data streams that were otherwise incomplete. A common type of data which is used to assess the numerical profile of underlying stock numbers by proxy is a quintessential fisheries metric known as Catch per Unit Effort (CPUE), which, in a longline context for a given area, is found by species catch (C; in number of individuals) for a specified period of

Figure 46. *Manta birostris*, Quartered (photo by author, Chennai. 2016). Spot-free ventral patterning, dark mouth, and distinctive and white "T" formed by negative whitespace on underside lets the observer know to which species of manta this specimen belongs.

time by effort units, easily defined as number of individual hooks (or 100's of hooks, etc.) in the case of longlining. However, any arbitrary unit of fishing effort is of course gear dependent, so, when comparing catch time-series generated using different gears from different studies, the respective CPUEs must be standardized, which can sometimes prove analytically difficult. Choosing for a moment to conscientiously avoid the ongoing meta-debate in the literature as to actual a validity and reliability of the numerical construct of CPUE itself (Harley, Myers & Dunn, 2001; Maunder et al., 2006) as an indicator of abundance, it should be conceded that CPUE does constitute perhaps one of the most classic of fisheries science metrics commonly utilized and is well established as a pillar of observational fisheries assessment in the literature.

The basic logic of CPUE as an indicator of abundance is that catch efficiency will decrease in proportion with the numerical decrease in the underlying stock size, all things held equal, and essentially (by)catch totals will take on the properties of underlying stock dynamics which may be estimated from their assumed proportional relationship (Dunn, Harley, Doonan, & Bull, 2000). Although logical, many caveats exist which usually must be accounted for in some fashion in order to derive credible estimates; though, the topic is probably among the most well researched in all of fisheries science and theoretical innovation is still ongoing (Maunder et al., 2006). If appropriate CPUE data streams for the Indian LL fishery had been identified outright in a relatively consolidated manner, it may have taken over the role as core metric around which any research design would have been modeled. However, such as it were, since many of these types of CPUE data-series with respect to our stocks of interest could not be located or where thought not to exist early in the discovery and design process for the study (or were otherwise deemed insufficient in some capacity), different core theoretical strategies and affiliated data types were ultimately employed, namely the SAFE data-limited longline bycatch assessment methods designed by Shijie Zhou and his various co-authors (Zhou et al., 2007, 2009, 2011; Zhou & Griffiths, 2008; Zhou & Fuller, 2011; Zhou, Fuller, & Daley, 2012). As previously stated, although some pieces CPUE data were identified from the outset, overall, what was immediately available was judged to be insufficient for application within many more traditional frameworks, a therefore the decision to seek novel alternatives was ultimately made early in the research design process as a matter of necessity, and greatly affected the downstream identity of the project.

However, after negotiating the literature over the entire arc of the research project and finding relevant new resources periodically, my initial claim "of insufficient oceanic longline fishery CPUE data" should perhaps be updated to a slightly more tempered position. There may be sufficient data spread among various publication to plausibly furnish a viable evaluative pathway, though, still not in a manner easily wielded, aggregated, or organized for that matter. This is not in any way intended to devalue the legitimacy of the area relationship method used as a proxy in this study, but rather to leave the door open for the possibility of further review of the comprehensiveness and ultimate tractability of any downstream utilization schemes for this class of data (i.e., CPUE studies) in relation to any arbitrary analysis of the fishery. Elements of the total CPUE data suite, should they be effectively aggregated, could even be directed into the analysis as it stands, albeit with some innovative redesign required. Like Cortés et al. (2015), total hook counts for a time period in question could be prescribed to their relevant cell-wise areas of geographic deployment to further and more specifically weight Availability calculations (or $A_{i,f}$ / $A_{i,J}$). This would mathematically ensure that fishing effort density effects would be taken into account, which, in the case of our specific research, would give greater value to cells (0.5° Lat × 0.5° Long grids) privy to more than one fishing station in a given time period and thus shape the final summation value accordingly for density effects of fishing effort rather than mathematically discounting by this data dimension/consideration. However, this data dimension as it is recorded across the literature, although plausibly extant, is still not considered easily implemented as it now stands and would require further innovation and refinement in this study's analytical program. For studies containing some defined time-series values for YFT and or Shark CPUE/Hooking Rate/Catch Rate see: Bhargava, Somvanshi & Varghese (2002); Somvanshi, Varghese, Rajkumar, Rao, & Gopalakrishnan (2005) [IOTC-2005-WPBy-16]; John & Varghese (2009) [IOTC-2009-WPEB-17]; Sinha, Pandian, Pattanayak, & Kar (2010); Kar, Govindaraj, Prasad, Ramalingam, & Blair (2011) [IOTC-2011-WPEB07–19]; Promjinda & Chanrachkij (2011) [IOTC-2011-WPEB07-48]; Varghese et al. (2011) [IOTC–2011–WPTT13–18]; Anrose, Babu & Sinha (2013) [IOTC–2013–WPTT15–45]; Varghese, Vijayakumaran, & Gulati (2013) [IOTC–2013–WPEB09–36]; **10.** Pillai & Satheeshkumar (2014); Gulati & Premchand (2015) [IOTC–2015–WPTT17–24]; Kumar, Pravin, Khanolkar, Baiju, & Meenakumari, (2015a); Kumar, Pravin, Meenakumari, Khanolkar, & Baiju (2015b); and Varghese et al. (2015).

Outstanding 13 Species for Calculation of F_{msm}, F_{lim}, F_{crash}—Rationale

Of the original 30 species flagged for membership within the "Oceanic" shark community of the Indian Seas (not including *C. hemiodon*), in addition to the calculation of instantaneous fishing mortality (F), only 17 ultimately were subject to a calculation of F_{msm}, F_{lim}, F_{crash} and thus a final status designation. The reason for this was simply due to time constraints. Although some amount of yet undone literature review and aggregation would be necessary in determining core vital parameter values for those remaining species, which may then be used in deriving the F_{mgmt} and Natural Mortality estimators—themselves being mobilized as pseudo-observations to populate the Bayesian hierarchical models as data which may ultimately derive the marginal posteriors of these parameters—there was no conceptual or procedural reason for their specific omission, other than basic temporal constraints.

In effect, the remaining 13 species are at present primed for analysis (i.e., garnering F_{msm}, F_{lim}, F_{crash} for those *spp*.). Although initial time dependencies have been cited as the only barrier to ultimate calculation of any of the remaining outstanding species, insurmountable data paucities may still be operational though at the moment remain unknown.

Post-Capture Mortality Estimates—Overly Precautionary*?*

One of the outstanding concerns in the relevant scholarship in general is the fundamental accessibility and reliability of data-limited estimation schemes in relation to some of the catch mechanism variables (q_i^h, q_i^λ, PcM_i); this will be framed both broadly and in specific cases of interest germane to this present study. Such as it is, widely divergent estimates have been noted in regard to the value of post catch mortality for a number of identical species evaluated via different studies, in relation to different regional fleets (Table 23).

Values from Cortés et al. (2010), Murua et al. (2012), Gallagher et al. (2014) and Cortés et al. (2015) are compared in Table 23. These studies hail from different regions and are defined by their constituent fleets' practices, which may plausibly be a primary driver of disparity among values, stemming from divergent real-world conditions.

Table 23. Comparison of post-capture mortality (PcM) values for shark species among studies.

No	Species Name	FAO Code	Post-capture Morality				
			Cortés et al. (2010)	Murua et al. (2012)	Gallagher et al. (2014)	Cortés et al.(2015)* Atlantic (general)	
			Atlantic Ocean	Indian Ocean	W/NW Atlantic	North	South
1	*Sphyrna lewini*	SPL	0.83	0.875	0.541	0.224	0.100
2	*Prionace glauca*	BSH	0.79	0.984	0.151	0.863	0.925
3	*Carcharhinus falciformis*	FAL	0.86	0.99	0.422	0.875	0.760
4	*Carcharhinus longimanus*	OCS	0.77	0.974	0.257	0.888	
5	*Galeocerdo cuvier*	TIG	–	0.903	0.032	0.030	
6	*Carcharhinus obscurus*	DUS		1	0.279	0.175	
7	*Alopias vulpinus*	ALV	0.18	0.18	–	0.825	
10	*Sphyrna mokarran*	SPK	–	1	–	0.500	
11	*Isurus oxyrinchus*	SMA	0.92	0.994	0.286	0.925	
12	*Isurus paucus*	LMA	0.88	0.992	0.511	0.850	
13	*Alopias pelagicus*	PTH	–	1	–	–	
14	*Sphyrna zygaena*	SPZ	0.85	0.997	–	0.863	
17	*Alopias superciliosus*	BTH	0.78	0.97	0.517	0.650	
25	*Carcharhinus plumbeus*	CCP	–	1	0.267	0.175	
45	*Carcharodon carcharias*	WSH	–	N/A	–	–	
46	*Carcharhinus signatus*	CCS	–	–	0.67	0.413	
47	*Lamma nasus*	POR	0.53	0.905	0.214	0.850	
48	*Pteroplatytrygon violacea*	PLS	0.18	0.37	–	0.025	0.025

Note. Species designated by red numerals (nos. 45-48) were not included in any analytical considerations of this study; as such, they are not found in Table 5 in Chapter I, which outlines core species flagged for research (spp. nos. 1–31), the species no. reference key in Chapter V, nor in Ancillary Appendix 1, which outlines additional species of note within the Indian oeanic fishery (Table A1–1 comprises spp. nos. 32–44). They are therefore given unique numbers which are greater than any of those listed in the aforementioned tables/chapter to avoid numbering conflict. *Cortés et al., 2015 is an updated study of Cortés et al., 2010; the express purpose of the former being a refinement of preliminary findings of 2010 utilizing additional data streams and analytical considerations, ergo the 2015 study should likely be viewed as the definitive set of results for the system. However, the change in values evinced by revisions to prior methodology is noteworthy as to communicate ongoing uncertainty regarding appropriate framework for furnishing these Post-Capture Morality values, and plausibly the regionally couched or fleet specific impact on values.

The specific nature or imperative by which these disparities exists has not yet been totally accounted for (though certain explanations will be posited), as values utilized within this study were either expressly published in relation to empirical data from the Indian Ocean region (Murua et al., 2012) or otherwise granted a value (using the somewhat precautionary strategy outlined in Zhou et al., 2011), when no relevant data had been published previously. The large portfolio of observations needed to furnish an evaluation that would increase relevant knowledge even moderately above a precautionary stand-in framework to allocate values for this variable is often the immediate barrier to entry to empirical work in this regard.

Effector mechanisms in Post-Capture Mortality. A wide confluence of factors ultimately play a part in determining the final mortality status of an organism once it interacts with gear; the extent to which these considerations are brought into modeling this process is a subject of ongoing research and debate, as well as being generally driven by data availability, which in many cases may either be partial or just completely non-existent in a data-limited setting. If one were implementing a direct empirical study for Post-Capture Mortality (PcM) for a particular species, test catches in combination with fishing logs are usually required to furnish data such as: number of kept (K) organisms, organisms discarded dead (DD), cryptic mortality (fish that died but otherwise slipped the line pre-haul, via predation of on-line corpse, or other largely stochastic physical encounters [this interaction can never be explicitly observed however]), at-vessel mortality (the proportion of animals found dead upon gear retrieval; pD), lost organisms (L) (i.e., slipped the gear) and estimate of condition of unknown (U) mortality status thereof (Cortés, 2015). Species specific factors may also come into play such as temperature shock effect, or active vs. ramjet gill oxygenation strategy of specific species (making the inability to move freely more traumatic or deadly in the case of the later; Gallagher, 2014). Last and of particular importance is of course the human agency which ultimately results in an organism being kept or discarded, as there is no operative “law of nature” which may adequately predict this outside of regional and fleet specific tendencies. The closest thing to this is the assumption that specific species subject to certain protections or expressly defined as non-target would be discarded due the classically straightforward, but probably inadequately nuanced, economic consideration that would prioritize vessel space to the highest value catch, which is consequently the target species, such as its purpose as the "target". This may be true in abundant stocks where high, long-term catch rates occur (viz., in a fishery where a fisherman assumes that he will be able to fill all possible vessel volume with the most valuable commodity and thus auto-eject anything boarded of lesser value); however, this paradigm may neither accurately reflect the current state of the Indian Ocean pelagic YFT stocks nor the predominant fisheries practices driven by ascendant market conditions of the region in question, India.

Indian bycatch discard trends. In recent years, a greater tendency to keep all landed fish has been observed in Indian waters, at least in coastal regimes and by trawler fleets (Bhathal, 2014). Although less well documented, it may also be reflected in the prevailing sensibilities in the domestic longline sector as well (Varghese et al., 2015), though unknown for the international fleet, which may theoretically still actively practice finning and at-sea discard of carcass. Given the lack of direct domestic landing from this fleet, it is hard to say what they are exactly doing with the shark bycatch that they necessarily would encounter, which does seem to be strangely underreported in a variety of examples.

In effect, all classically defined incidental catch or bycatch may simply be kept as byproduct in many circumstances (Ardill et al., 2013), including pelagic sharks. Albeit most reporting of this wholesale retention phenomenon has been in relation to the trawl sector, the uptick in this practice is being fundamentally driven by a changing, demand-side purchasing environment in the domestic context. Given the large and growing aquiculture industry of the country, essentially all biomass has a viable price point if returned to port, were it will either be turned into fishmeal or other processed products relevant across a wide spectrum of the agricultural industry, as well as be utilized to some degree by endemic and impoverished sectors of the constituent population as a cheap protein option.

Additionally, shark meat has always been a relatively popular product in India, so large sharks may be reasonably valuable and worth retaining into port (Varghese et al., 2015). Value is not necessarily lost with these fish, which may otherwise be considered trash or discard species in a global context, so they will be retained as a form of financial risk management against a bad set, which are becoming more frequent. Therefore, the expectation of release, regardless of living or otherwise because a species is not explicitly a target specimen is somewhat problematized in the India context, generating a more ambiguous discard condition than may perhaps be observed of equivalent fisheries in other global regions. At least when there exists no specific protection to a certain organism or class (assuming unsupervised rule following generally prevails at sea, which can be hotly debated), the concept of "trash fish" or auto-discards in the Indian context is seen to be in decline (Dineshbabu, Thomas, & Radhakrishnan., 2012; Dineshbabu et al., 2014).

Given this trend, nearly all catch will be landed in certain sectors under a variety of conditions. This is especially the case in the large trawling sector of the domestic fishery, which operates more inshore, though, is currently in the process of redefining itself with the advent of new deep-sea methods and will likely become a facet of the oceanic regime in the near future as the coastal trawling fleets update and shift fishing ground in relation to the quickly depleting inshore areas, which have been trawled excessively for years.

With these considerations in hand, the decision to designate a precautionary value range (.666-.999) for unpublished species is defensible by-and-large, although it may over inflate impact and thus risk scores (stock status designations) for specific species which may have a relatively high chance of survival, given that they are actually discarded. In effect, the transferability of PcM across regional constructs is difficult to appropriately frame. Such as it is, empirical results for this variable where used for all available sharks as calculated by Murua et al. (2012).

Tiger shark (G. cuvier) post-capture robustness. There are however some significant discrepancies in values that should be taken into consideration (Table 23). Post catch mortality is very different for *G. cuvier* and to a lesser extent *C. obscuras* in between Atlantic and Indian Ocean fleets; Gallagher et al. (2014) cites the tiger shark as an extremely hardy species somewhat impervious to post capture mortality, where Murua record the species at around 90% Post-Capture Mortality Rate. If an intermediary value defines the true reality, then it may be acknowledged that PcM for the Tiger shark, in the context of results derived in this present study, may be somewhat precautionary/ to overly precautionary, and may be adjusted accordingly in the future.

Pending Regional Expert Review & Stakeholder Consultation

As with many analytical processes in fisheries science and analysis, expert opinion and override tend to be critical fail-safes in maintaining outcome validity of model-based assessments, especially as some models/methodologies or calculations may be intrinsically blind to certain on-ground realities (or inversely completely overrepresent minor phenomenon). Specific knowledge of these on-ground realities, which may have been interpreted or framed in one manner or the other by the designer of the model (for example, perhaps unsuccessfully due to incomplete knowledge or unpublished nature of some minor detail), is often gleaned only from the long-form and consistent observation of a system by a regional expert, which is why consultation and review is always seen as final, necessary imperative when moving from model results to policy intervention of advocacy. Given that the author's knowledge is built on the extent and clarity of literature (such as it is) and brief field exposure, review by a regional or set of regional fisheries professionals with knowledge of elasmobranch bycatch in the Indian Tuna fisheries, expressly to flag false-positives manifest in the results, would be highly desirable.

Although less of an issue in this study, as it delves only briefly into policy prescription and remediation design, a formal mechanism of stakeholder engagement is desirable, whereby results are communicated mainly to the sector's actors with the expectation and facilitation of feedback before and during the communication of policy recommendations, as all parties fundamentally and ethically need to be involved in designing and executing changes in fisheries frameworks (Hobday et al., 2011).

Miscellaneous Considerations

The following final few sections round out the full scope of topics encountered over the course of this research venture which merit coverage in the consideration of the fishery at large.

Recent Emergence of Deep-sea fishing for Chondrichthyan Resources

Deepwater sharks are known to suffer from population depletion via extractive fishing activity with greater intensity than those occurring in other ecosystems, due largely to these specialized organisms' even more depressed fecundity than their in-shore and shallow dwelling allies (Rigby & Simpfendorfer, 2015). Specifically, because deep-water sharks live in cold and possibly food-limited environs, these highly specialized organisms often exhibit slower-than-average growth and reproduction rates, likely due simply to slower overall metabolism resulting in a longer (and therefore slower) life-history cycle with the added effect of having less energy per cycle to invest in offspring. Moreover, these species are usually so environmentally removed from the visible surface action and mainstream stock oversight (in many localities at least) that, as is often the case, considerable impact has been wrought before any stakeholders have had time to implement a viable management framework, usually only spurring notice as advanced stages of population decline become evident in a very short time window, as was the case in the Maldives in the early 1990s (Anderson & Ahmed, 1993). In summary, the total constellation of factors makes deep-water sharks potentially much more prone to overfishing and subsequent population collapse than shallow water sharks, and due to their slow lifecycles, potential rebound is often mathematically relegated to the passage of many decades to centuries possibly.

Akhilesh et al. (2011) as early as 2008-’09 had noted the change and/or opening of targeted deep-water Chondrichthyans fisheries for Gulper Sharks in South East India. Since 2000, Indian shark fishermen have been noticed in shifting their fishing operations to deeper/oceanic waters by conducting multi-day fishing trips, which has resulted in considerable changes in the species composition of the landings, evident via direct comparisons to landings reported for similar locations in the 1980s & 1990s. A case study at Cochin Fisheries Harbor (CFH), southwest coast of India during 2008-2009 indicated that besides the existing gillnet-cum-hooks & line and longline fishery for sharks, a targeted fishery at depths >300-1000m for gulper sharks (*Centrophorus spp.*) has emerged (Akhilesh et al., 2011). As this fishery is now under harvest pressure, lessons may be learnt in the form of necessary preemptive fishing controls on this stock in contrast to the unregulated situation that led to the ultimate crash in deep-water shark stocks in the Maldives in the late 1980’s early 1990’s (Anderson & Ahmed, 1993), specifically targeting deep-water Gulper Shark (*Centrophorus spp.*). In this latter case, the fishery was exploited and heavily overfished within a matter of a few years, the stock arcing from discovery to overfished to depleted largely before it was even officially acknowledged as extant in any management capacity (Anderson & Ahmed, 1993).

Future Expansion of Small / Medium Sized Domestic Longline Fleet

According to recent reports, the fleet of small- / medium-sized domestic longliners is currently in the process of receiving an incredibly large financial and capacity expansion. According to announcements made in May of 2017, a large expansion to this general initiative (though, at this point having been taken up by several non-original actors) is currently underway. This initiative plans to convert some 2000 trawlers to deep seas vessels (tuna longliners and drift gillnetters) in the next four years (by 2020), subsided by both State and Union government to a tune of 70% (Anon, *Times of India,* May 2017). This development has the potential to significantly change the profile of the oceanic fishery, and its progress should be monitored with acute interest.

Selected Species-Specific Comments

Although presently given a Data Deficient Status by IUCN, *C. granulosus* has recently been subject to taxonomic revision, where both the formerly localized sister taxa of *C. niaukang* (Taiwan Gulper Shark) and *C. acus* (Needle dogfish; タロウザメ) have been found to be non-distinct via molecular analysis (Straube et al., 2013; Straube, Corrigan, & Naylor, 2013) and thus all revert to the senior synonym of *C. granulosus* as a unified species (White et al., 2013). This change is still being negotiated in some major databases and may likely be credited as the primary instigator of the DD status as it now stands according to the ICUN Red List designation scheme. This study may however establish an interim risk level assessment for the region, certainly the first of its kind in this specific geographical context.

The status determination of *S. lewini* at precautionary medium risk may have been too low considering all the knowledge on present sustainability and conservation trends regarding the species. It is known that the scalloped hammerhead is a highly common species to be caught as bycatch in regional longline, yet it is designated as ICUN

"Endangered". At the very least, the status designation as it stands should be viewed as a theoretical floor value, and the Indian Seas stock may be in a greater risk position than that which has been calculated within this study. This ascertainment may be viewed as an escalation of most recent "Non-Detriment Findings" (NDF) assessment carried out for *S. lewini* in relation to the Indian seas as a stipulation of India's membership as a party to CITES, which prescribes the "Severity and geographic extent of conservation" as "Medium" (Zacharia et al., 2017). In general, for both this study and the NDF assessment, data unknowns may be masking true extent of catch and mortality impact on the species in the region.

Study Recommendations for Shark Risk Remediation and Sustainable Fishery Development

This final section may be seen as a summary or set of take-aways and policy recommendations accrued via my in-depth, multi-year exploration of the 21st century fisheries of India, with respect to the sustainability and conservation potential of Elasmobranchii in the world's second most prolific shark catching nation. They are presented in no particularly formal order; though, each recommendation should hopefully harken back to a notable point or significant insight made within the broader text, which likely will have been raised at various opportunities and ring familiar to the reader. This list is also nowhere near comprehensive, but trends towards an emphasis on attainable actions, structural critiques, and a healthy admixture of novel ideas.

- Implement monitoring and data aggregation improvements for longline shark bycatch.

- Establish a fishery monitoring protocol which counts landings in a species-specific manner for elasmobranchs. Although strategically difficult admittedly, any modest improvement would be greatly beneficial. Perhaps it could be implemented for at least very conspicuous species, such as Hammerheads (Sphyrnidae) and Threshers (Alopiidae) which are largely unmistakable, at least in relation to other families of sharks though much less so within their respective groups.
- Establish a monitoring protocol such that the recent discontinuation of international lease charter program (LOP Program) of vessels is *actually respected* by former participating vessels.
- Rather than rely solely on external and largely independent actors to produce assessments pertaining to the politically “hot”/controversial/undesirable topics, particularly IUU fishing (and to some degree the history and status of the shark fin trade in the country in light of the recent ban), relevant governmental organizations should take ownership of quantifying the problem and conducting relevant research, regardless of inherent, perceived sensitives and in a transparent manner. In this vein, and because they are best equipped to adequately accumulate and utilize such data, government-fisheries-science agencies (likely the CMFRI, FSI) should initiate a quantitative assessment of IUU fishing in the greater Indian marine fishery and oceanic region specifically and utilize said findings in honest policy recommendations which adequately take into account the scope of IUU fishing, a line-item which seems to have been largely discounted or fully ignored in the calculation of yield (at least in public facing documents). If such organizations are truly science driven, there should be no true conflicts of interest.

- Concentration on Andaman & Nicobar Islands policing and sustainable fishing regulation: as the area remains a hotspot for IUU fishing in the region, is still subject to relatively low-levels of fishing effort (compared to mainland), and houses a large diversity of regional oceanic sharks, whose numbers still may be moderately healthy. Establishment of MPA (marine protected areas) and larger marine reserves in high-value conservation areas of the A&N waters before the true escalation of fishing pressure inevitably happens in this area, this preemptive action may ensure a satisfactory management outcome as well as establish a high-standard conservation paradigm before many livelihoods depend on high-extraction fishing in these waters.
- Consign retrospective calculation of catch totals of international fleets, under the assumption of significant underreporting, by a government scientific agency, as there seems to be an institutional hesitance to engage the issue given political nature of the connotations. As it stands, there seems to be significant numerical discrepancy between the number garnered in the independent literature and that which has been furnished by the governmental fisheries science organizations. Such a condition was clearly exposed during the recent court saga pertaining to the management and continued allowance of LOP fishing, and should be rectified accordingly, both for the benefit of science and effective fisheries management in the Indian EEZ but also to restore credibility in the eyes of the fish worker community through accountability for administrative mistakes made. The continued cooperation of this focal workforce in sustainable development of the effected fisheries/sectors is vital both presently and for the future of productive rapport, as they will certainly be asked to furnish many management requests.

- Promote better relationships and data exchange as it pertains to fisheries research among India and its regional domestic neighbor's relevant scientific agencies (Pakistan, Sri Lanka, Bangladesh, Iran, Maldives, Myanmar, Thailand, Indonesia etc.) as well as multinational scientific organizations (IOTC, FAO). Although significant geopolitical tensions exist among many nations within the region of South Asia, especially as it pertains to territorial and resources disputes, perhaps this vector can exist outside of such considerations, and in turn be useful to regional cooperation in more ways that simply fisheries management, albeit in a minor though productive manner.
- Curtail the promotion of oceanic shark stocks as underutilized and a potential fisheries resource within the Indian seas. This notion is frequently presented in many official publications; though, it is highly recommended that such a strategy be abandoned.
- Increase professional education as to the present imperiled status of sharks in the fisher and or industry worker community, as they might be motivated to release non-critical incidental bycatch. Additionally, education as to the limited actual danger of sharks may frame the class more positively, and thus increase willingness to engage in such management requests.
- Similarly, consider the proactive incentivization of increased post-capture release schemes of bycatch / incidental catch sharks in tandem with education; however, it is acknowledged that shark meat is utilized for nutritional needs and in a mostly non-wasteful manner (outside of at-sea finning, which is presently banned) within the context of India. In this way, via a reduction in mortality from the total collection of

fleets and actors (not just longline) contributing to the overall harvest management through modest reduction due to increased release, traditional targeted shark fisheries (such as those based out of Tuticorin, etc.) may be maintained, so long as there are no efforts to greatly expand them, and thus equity may be maintained among longstanding actors despite shifting management needs and concerns. A specific study may be necessary to quantify contributions at a sector level and thus determine the efficacy of this suggestion.

- Consider an international apprenticeship program to facilitate the increased knowledge transfer of best-practice and next generation fishing practices back to India. Essentially, this would actualize the core intangible goals of the LOP program—that is, of knowledge transfer back to the domestic fisheries once individuals having completed such apprenticeship return home, without the significant drawback of largely unregulated fishing allowances by international fleets with little connection or interest in domestic affairs within the EEZ. Given their common standards of practice, significant national interests in sustainable management of natural and biological resources, history of good faith scientific cooperation, and commendable human-rights record on the high-seas, Australia, New Zealand, Iceland, and Norway could easily emerge as a shortlist of potential collaborators, though certainly non-exhaustive. Payment for such apprenticeships at destination market rates, subsidized by some contribution agreement of the two parties, would be expected. Marketing such a venture as action aligned towards the recently adopted UN Sustainable Development Goals of 2015 (SDGs), specifically no. 14, could be beneficial in drawing interest. Also, combined with India's natal scientific and engineering capacities, there is opportunity for the development of a small, though highly skilled, next-generation high-seas fishing and resource management skill hub with respect the greater south Asian region, with a workforce able to operate internationally and set the development pace and best practice for other Indian Ocean coastal states.

- Consider a full or partial moratorium on the targeted harvest of true deep-sea sharks, such as the gulper shark and other allied species. The capricious reaction of such shark species to even modest amounts of fishing pressure places them in significant risk, with the majority of damage to stock integrity usually realized well before managers have a chance to properly assess scope and promote harvest controls. The present limited and nascent character of the fishery may make this process more feasible and less of a hardship on participants; though, a full stakeholder consultation would be necessary before any actions occur.
- Consider implementation of a catch quota for sharks in the Indian seas.
- Update domestic laws and protection schemes to be in line with sharks given specific protection under international agreements, i.e., consider moratorium on landing and post-capture release requirements of all sharks subject to CITIES and CMS protections, as well as all those that are recipients of at least “Endangered” status under the ICUN.
- Prioritize the adoption of an NPAO-Sharks for India. At present the nation remains the world’s most prolific shark fishing nation without such an apparatus, and nearly 20 years tardy in its supposed submission.

- Additionally, India should consider joining as a member party to the CMS's additional protective instrument regarding migratory sharks, established in 2010: Memorandum of Understanding on the Conservation of Migratory Sharks (SHARKS MOU).
- Consider a ban on the catch of all hammerhead sharks. Their class-wise threatened status, small value to overall commercial yield, and distinctive morphology could make this feasible. Additionally, a ban on all hammerheads would eliminate the need to differentiate between the species at sea, which has historically been a problem in many contexts.

Conclusions

Overall, this study met its stated analytical goals of producing quantitatively derived stock status assessments for many species of oceanic sharks on a species-specific basis in a particularly data-sparse sector within the total Indian marine fishery. Novel methods were required to produce these outcomes, and both the development and successful implementation of such a methodological framework represented a core conceptual advancement for the study of this region in particular—moving the proverbial needle from unknown to that of a newly quantitative baseline. This study upgraded present knowledge about the oceanic fishery in relation to the prevalence of shark bycatch mortality through longline fishing, which was determined to be largely unsustainable for an overwhelming majority of species analyzed. Many other relevant values were also produced for the first time ever in relation to this fishery through the efforts of this study, which will hopefully be of value in the scientific advancement of the fishery and the formation of revised policy for longline fishing in the Indian oceanic EEZ.

The combined shark mortality for the totality of Indian economic waters, which would be defined as mortality accrued by all relevant fishing gear types (not just longline) with respect to all relevant geographic sectors of the total EEZ (coastal & oceanic) is the eventual goal towards providing a fundamental baseline understanding for all sharks in the Indian EEZ and in every part thereof. Due to significant convolution persistent in the coastal fishing sector, stemming largely from the mixed-species, mixed-gear, and mixed-fleet identity of the inshore domain (as well as the disparate data regime arising therefrom) such a geographically contiguous and wholistic assessment of the total Indian shark harvest was intractable in the course of one research thesis.

Although such a condition acted against the goal of stock status assessments for all species extant within any sector of the total EEZ, shark mortality was able to be calculated for a specific and significant sector, oceanic longline bycatch, due to the fact that it entailed much more well-defined boundaries and definitions across a number of data dimensions (being defined primarily by a single gear for a single target species, yellowfin tuna) than its coastal counterpart. Ergo, despite ostensible limitations, by correctly bounding the scope of the analysis, a significant—and largely hidden and under-researched—vector of shark bycatch mortality in the oceanic longlining sector was quantified, in turn enhancing the understanding of the impact of the nation with the world's second largest shark harvest. Full production of SAFE risk designation for at least 13 sharks are still outstanding, and may very likely be the basis of connected, follow up research.

The hypothesis of unsustainable fishing in the oceanic longline fishery was confirmed through the properties of statistical analysis espousing a high degree of confidence in its results. Additionally, it may be confirmed that the sector is experiencing similar or more intense impact than that of global background levels, a claim based largely on the number of extreme high risk and other higher risk SAFE designations from among the 17 completely evaluated species. However, given the data paucity of the fisheries data environment, certain analytical work-arounds were employed which may have deteriorated or inversely, overly (and unfairly) strengthened the mean signal among the many various data input vectors, the nature and scope of which cannot be truly known under the present circumstances in the absence of empirical follow-up. Additionally, no model should be assumed a perfect representation of phenomena under consideration, and therefore any model should always be considered working, best understandings (or best current drafts) of the system of phenomena in question. Specifically, in the context of Bayesian inference, model construction is often just as much influenced by human preference and analytical efficiency considerations than by other purely mathematical or "total correctness" based characteristics, the former working against total theoretical complexity and accuracy of the model for the sake of legitimate constraints on implementation practicality—that is, up to a maximum level of tolerable tradeoff (complexity [and possibly accuracy] vs. practicality), which is many times a decision that is either subjective and/or incompletely articulated. This study endeavored to be completely transparent and fastidious in the communication of all model construction decisions, though, there is always room for improvement.

In final consideration, when taking into account all of the abovementioned factors simultaneously in the final comprehension of model outputs, even if many of the final values may have been influenced by a number of precautionary considerations circumscribed in the model itself as a part of intrinsic design rationale or stand-ins for unknown values, the final severity of the SAFE designations garnered imply a condition of community impact that seems to greatly outstrip numerical inflation due to the activity of precautionary considerations alone and signal a highly probable, on-ground reality of unsustainable bycatch mortality for sharks in this sector. The outcomes of this research are therefore deemed to be viable and highly useful in the actual, specific guidance of the review/revision of certain policy initiatives and fishing practices in the region at a general level, even if the specifically implemented mathematical methodology could at times rightly be criticized as somewhat cumbersome and self-referential, considering the core subject matter being explored.

Regarding the policy initiatives broached, many of them were either informed by pre-study paradigms and therefore merit policy review, while others are envisioned to increase steadily over the next decade at least (in the case of the latter, i.e., fishing practices) as India continues to evolve all aspects of its extractive, commercial economy in lockstep with its prevailing socio-demographic transition, and in this particular situation, as it pertains to the increased extraction of the oceanic resources of its Exclusive Economic Zone. When pursing and revising fisheries policy in this sector, the government of India should consider well its commitments to international conservation agreements regarding certain focal and charismatic shark species, as well as at a general level the desirability of establishing a sustainable system of resource utilization in perpetuity for its marine ecosystems. This will ultimately work in the favor of national welfare, even if short-term tradeoffs must be negotiated.

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[*Note: Some family groups especially in Southern India do not actively bestow two formal names, as is likely the case with Premchand.]

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[* Some sources that were not referenced directly in-text but were otherwise of relevance may be listed herein for added utility in compiling and organizing sector knowledge for future use.]

Ancillary Appendix 1

Additional Shark Species of Note Potentially Active in the Oceanic Fishery (Table A1–1)

Table A1–1. Additional shark species of note potentially active in the Indian oceanic fishery.

	Name			Fisheries Profile (Total Indian EEZ)			Instrumentation for International Mgmt.				
Sp. No. [a]	Common	Scientific	Citation	Abundance in fishery [b]	Habitat / Geography [c]	Gears [d]	IUCN Status [e]	CITES Monitored [f]	CMS Protected [g]	HMS (Y/N) [h]	Sources [i]
32	Bull Shark	*Carcharhinus leucas*	(Müller & Henle, 1839)	****	Marine / brackish / freshwater, demersal, EC & WC	Longlines and hook & line	NT	–	–	Y	[Bhathal, 2014; Mohanrj et al., 2009]
33	Blackspot shark	*Carcharhinus sealei*	(Pietschmann, 1913)	*	Marine, reef associated, shallow water, EC & WC	Gillnets and hook & line	NT	–	–	Y	–
34	Grey bamboo shark	*Chiloscyllium griseum*	(Müller & Henle, 1838)	****	Marine / brackish, reef associated, EC & WC	Gillnet and hook & line	NT	–	–	N	–
35	Winghead shark	*Eusphyra blochii*	(Cuvier, 1816)	**	Marine / brackish, benthopelagic, EC & WC	Gillnets, stake nets, seines, longlines, and hook & lines	EN	–	–	Y	[Bhathal, 2014]
36	Snaggletooth shark	*Hemipristis elongata*	(Klunzinger, 1871)	***	Marine, demersal, EC & WC	Gill nets, bottom trawl, and longlines	VU	–	–	N	[Bhathal, 2014]
37	Hooktooth shark	*Chaenogaleus macrostoma*	(Bleeker, 1852)	****	Marine, demersal, EC & WC	Gillnets and longlines	VU	–	–	N	[Bhathal, 2014]
38	Tawny nurse shark	*Nebrius ferrugineus*	(Lesson, 1831)	***	Marine, reef-associated, EC & WC	Longlines, gillnets, fixed bottom nets, and bottom trawls	VU	–	–	N	[Bhathal, 2014]
39	Sicklefin lemon shark	*Negaprion acutidens*	(Rüppell, 1837)	**	Marine / brackish, reef associated, demersal, EC & WC	Gillnets and longlines	VU	–	–	Y	[Bhathal, 2014]
40	Arabian smooth-hound shark	*Mustelus mosis*	(Hemprich & Ehrenberg, 1899)	*****	Marine, demersal, EC & WC	Trawl and gillnet	DD	–	–	N	[Bhathal, 2014]
41	Whitetip reef shark	*Triaenodon obesus*	(Rüppell, 1837)	****	Marine, reef associated, demersal, EC & WC	Gillnets and longlines	NT	–	–	Y	[Bhathal, 2014]
42	Graceful shark	*Carcharhinus amblyrhynchoides*	(Whitley, 1934)	****	Marine, coastal-pelagic, EC & WC	Gill nets and longlines	NT	–	–	Y	–
43	Bignose shark	*Carcharhinus altimus*	(Springer, 1950)	*	Marine / brackish, reef associated, demersal, EC & WC	Longlines	DD	–	–	Y	–
44	Pigeye shark	*Carcharhinus amboinensis*	(Müller & Henle, 1839)	*	Marine, pelagic-oceanic, EC & WC	Longlines and drift gillnets	DD	–	–	Y	–

Note. **ICUN** = International Union for the Conservation of Nature; **DD** = Data-Deficient; **LC** = Least Concern; **NT** = Near-Threatened; **VU** = Vulnerable; **EN** = Endangered; **CR** = Critically Endangered; **CITES** = Convention on International Trade in Endangered Species of Wild Fauna and Flora; **CMS** = Convention on the Conservation of Migratory Species of Wild Animals; **UNCLOS** = United Nations Convention of the Law of the Sea; **HMS** = Highly Migratory Species;

NPOA-Shark = National Plan of Action for Sharks; **FSI** = Fisheries Survey of India; **WC** = West Cost [of India]; **EC** = East Cost [of India]; (*****) Predominant in commercial shark landings; (****) = Common occurrence; (***) = Moderate occurrence; (**) = Rare occurrence; (*) = Isolated reports only; (!) = Protected under WPA, 1972; (?) = Needs confirmation.

[a] The species table and affiliated numbering scheme picks up at no. 32, immediately following the number of the last shark on the primary oceanic cohort list (which is no. 31) in Table 5 (also reemphisaed in Table 17). No explicit analyses were conducted on the shark in this present table, though, they have elements of viability which could potentially be of intrest to follow up research, and as such, they were included as an additional resource.

[b] The data in column 5 is from Guidance on National Plan of Action for Sharks in India (p. 88-98), by Kizhakudan et al., 2015, Kochi, IND: Central Marine Fisheries Research Institute. Although general in nature, it is believed to be of use within the table assembly, which attempts to encapsulate all prior assessment criteria for key species of intrest. It should be noted that these values refer to species prevalence/abundance in the context of **the entire marine capture fishery** of the Indian EEZ, and not simply the oceanic tuna LL fishery of the Indian EEZ—albeit the latter is usually what is being referred to in terms of the scope for interpreted results of this study. These designations of occurrence within the Indian marine fishery may be misleading if a reader does not note which framing constraints are being employed.

[c,d] The values in and /or descriptions in columns 6 & 7 are taken from the same publication and figure as column 5, i.e., Kizhakudan et al. (2015) Guidance on NPOA-Sharks. CMFRI, 2015. They also apply to the entire marine capture fishery of the India EEZ, and not exclusively the oceanic tuna LL fishery of the EEZ. Otherwise, their interpretations are face value, where WC & EC refer to West Coast and East Coast of India respectively.

[e] IUCN Red List designations are up to date as of the 2017-3 iteration of the database.

[f] As no species assembled within this present table achieve a designation in the CMS category, see Table 5, p. 46, note (**f**) for a full description of this column and its interpretation if needed.

[g] As no species assembled within this present table achieve a designation in the CMS category, see Table 5, pp. 46-47, note (**g**) for a full description of this column and its interpretation if needed.

[h] The United Nations Convention of the Law of the Sea—**Annex I** (UNCLOS-Annex I) defines species that are designated as Highly Migratory Species (HMS). This designation eschews special legal relevance within parties to the convention (i.e. have a specific legal relevance above a biological one in some cases), as species with these designations are defined to exist between and across territorial claims and thus shall be managed as a transboundary stock. UNCLOS-Annex I expressly lists species that are privy to the official designation as a Highly Migratory Species. Within appropriate cells, species designated as an HMS via express inclusion within UNCLOS-Annex I are designated as such with a yes or no (Y/N).

[i] Studies / Sources where the fishery of the species was discussed in some detail, above and beyond the summary information provided in the Guidance on National Plan of Action for Sharks in India, Kizhakudan et al., 2015 (which mostly populated columns 5, 6, and 7). As these species were not the primary focus of this research, these listings of sources should not be inferred as all that was available after the conclusion of a comprehensive literature review effort for each species, as other publication likely exist with respect to this grouping of shark species and their intersection with India's oceanic fishery as well as the total marine fishery.

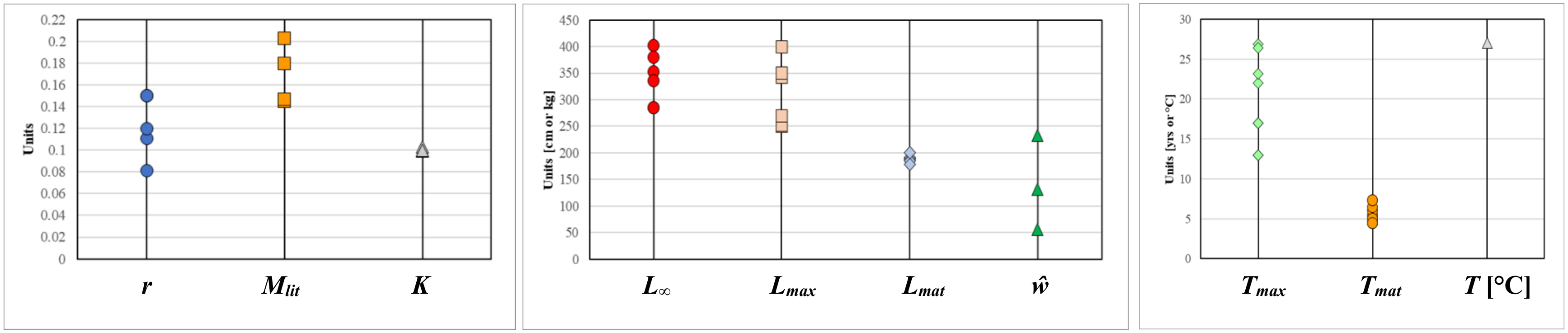
Ancillary Appendix 2

Vital Parameter Data, Biological Reference Points & Natural Morality Posteriors for Remaining 14 Species

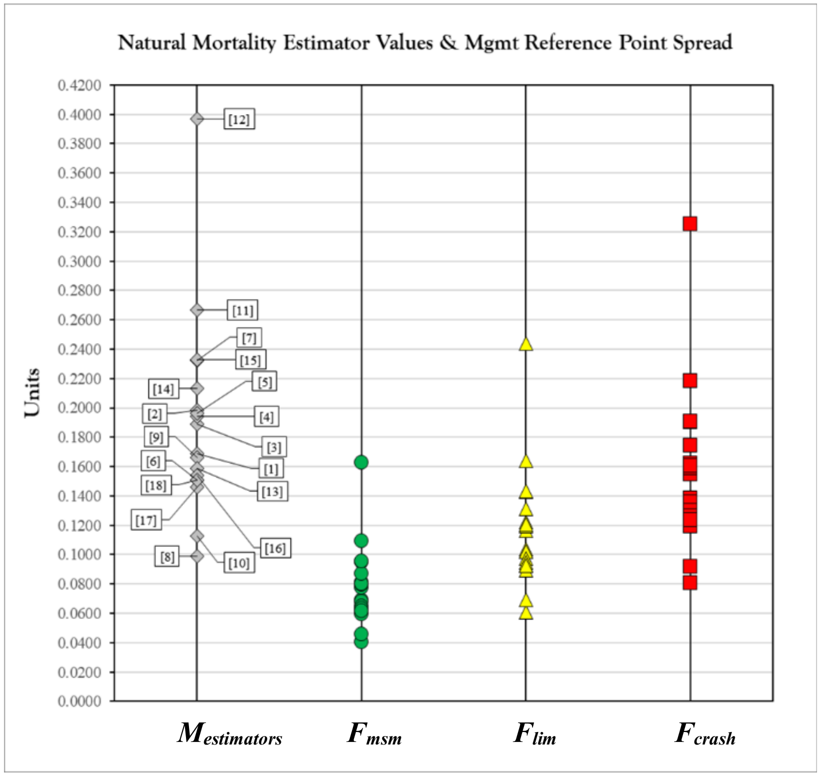
For *Sphyrna lewini*, *Prionace glauca,* and *Carcharhinus longimanus*, corresponding equivalent figures, as well as associated in-depth explanations of features and supporting concepts, can be found in Chapter III (Figures 27[a-d]–29[a-d]), Chapter IV (Figures 31[a-b]–33[a-b]), and Chapter V 36[a-d]–38[a-d] respectively. Figures for the remaining 14 species are given here in Ancillary Appendix 2, via two pages of figures (i.e. figure-sets) per species. Figures equivalent to those given in Chapters III & IV may be found on page / figure-set (a), and figures equivalent to those given in Chapter V may be found in page / figure-set (b). The reader should consult those previously mentioned positions in the main text if any contextual information is required, as only a minimum organizing framework is employed here with few auxiliary details. The labeling is as follows, A2 is the prefix for Ancillary Appendix 2 tables / figures, the number after the dash corresponds to the sp. no coupled uniquely with every shark species (see Table 17, Chpt. V), and the letter a or b represents figure-sets (a) or (b), which have 5 and 4 graphs/tables respectively. For page space efficiently, figure-set (a) combines the mini tables found in Figures 27d (or in 28d or 29d, just using 27d as example) with a second species specific table given in Figure 31b (or 32b or 33b, ect.). Otherwise, the graphics are replicated in their entirety here for these species as they were previously in the body of the text.

Figure-sets for these following species may be located via their correspondingly organized label nomenclature: *C. longimanus* (A2–4a, 4b); *Galeocerdo cuvier* (A2–5a, A2–5b); *C. obscurus* (A2–6a, A2–6b); *Alopias vulpinus* (A2–7a, A2–7b); *Centrophorus granulosus* (A2–8a, A2–8b); *Sphyrna mokarran* (A2–10a, A2–10b); *Isurus oxyrinchus* (A2–11a, A2–11b); *Isurus paucus* (A2–12a, A2–12b); *Alopias pelagicus* (A2–13a, A2–13b); *Sphyrna zygaena* (A2–14a, A2–14b); *C. brevipinna* (A2–16a, A2–16b); *Alopias superciliosus* (A2–17a, A2–17b); *C. limbatus* (A2–22a, A2–22b);*C. sorrah* (A2–26a, A2–26b).

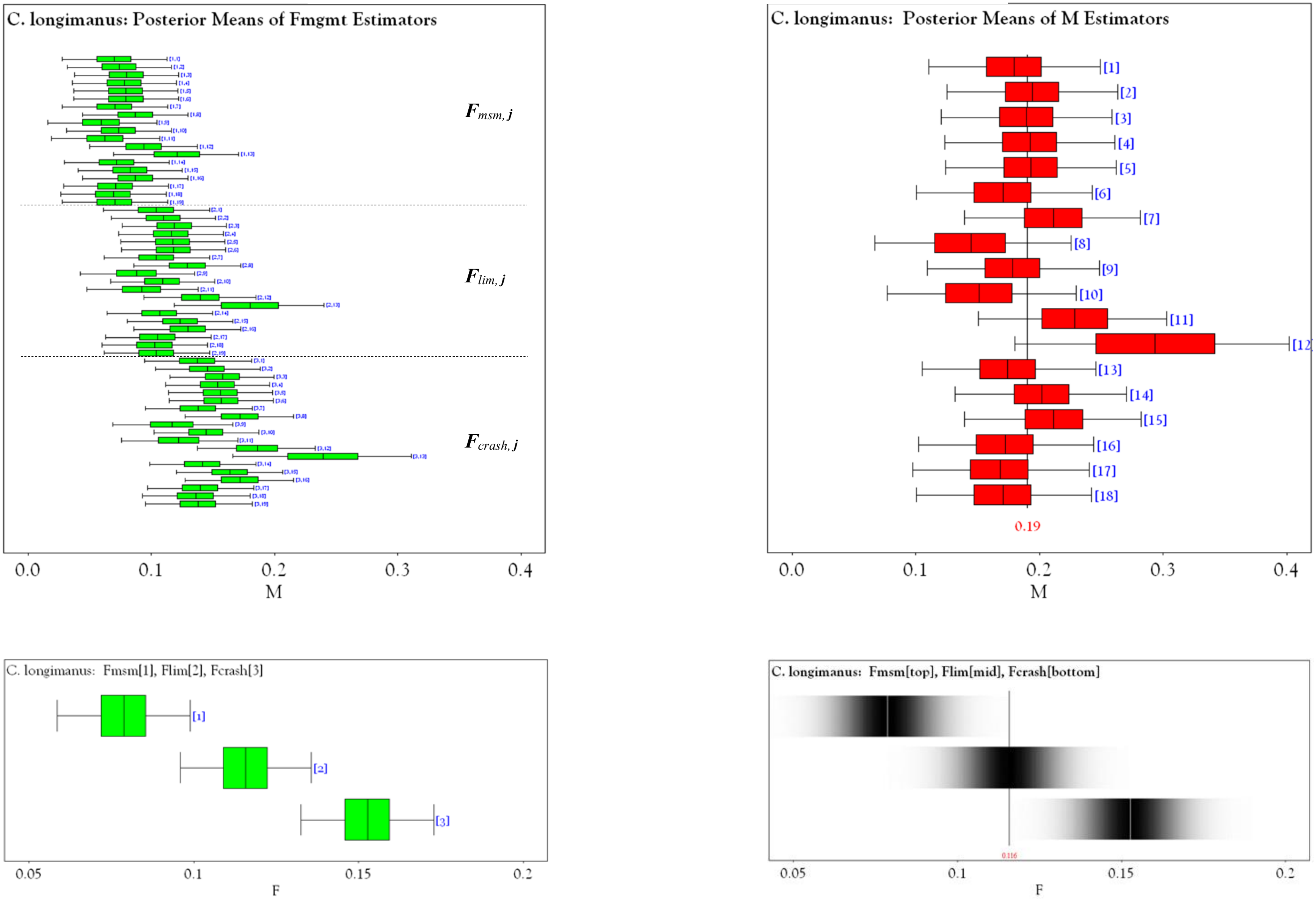
Figures A2–4a. *Carcharhinus longimanus* (Oceanic Whitetip)



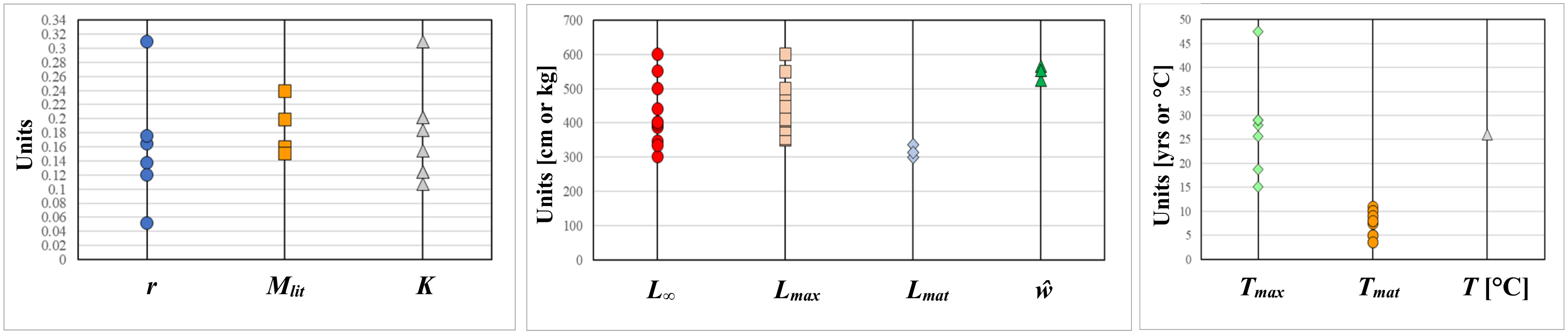
	n_{Total}	n_{Female}	μ	σ_{FW}
r	5	0	0.1223	0.0291
M_{lit}	4	0	0.1688	0.0279
K	3	1	0.1005	0.0017
$L\infty$	6	0	340.14	48.46
L_{Max}	8	2	291.53	52.74
L_{mat}	7	7	188.51	6.45
$\bar{w}$	3	0	140.26	88.56
(e) T_{Max}	6	2	19.80	5.58
T_{mat}	7	3	5.62	1.13
T [°C]	1	—	27.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1904	0.0667
F_{msm}	19	—	0.0772	0.0269
F_{lim}	19	—	0.1157	0.0403
F_{crash}	19	—	0.1543	0.0537



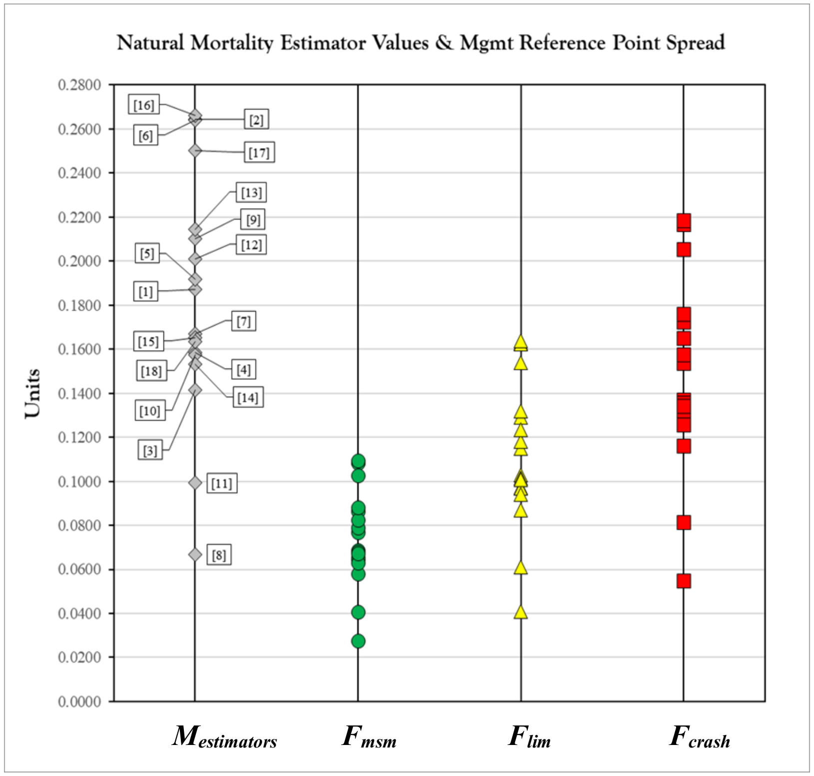
Figures A2–4b. *Carcharhinus longimanus* (Oceanic Whitetip).



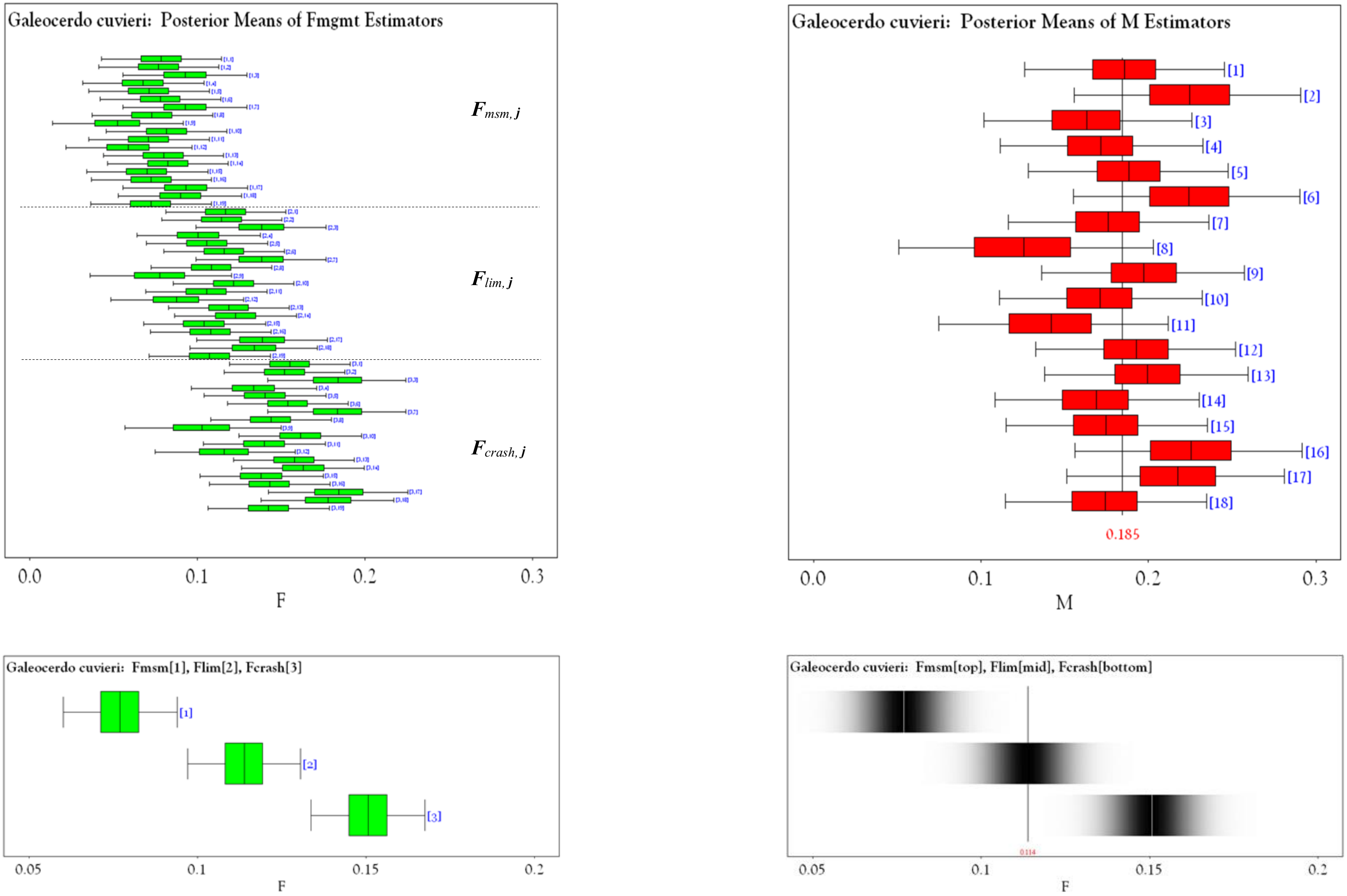
Figures A2–5a. *Galeocerdo cuvier* (Tiger Shark).



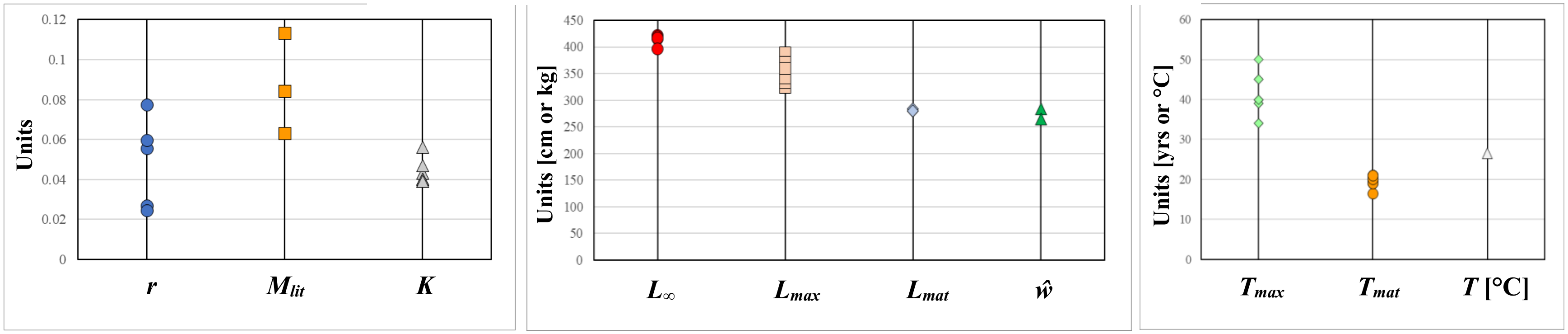
	n_{Total}	n_{Female}	μ	σ_{FW}
r	6	0	0.1597	0.0854
M_{lit}	4	0	0.1871	0.0403
K	6	2	0.1760	0.0654
$L\infty$	10	1	424.00	92.25
L_{Max}	17	10	439.37	61.52
L_{mat}	3	3	317.00	16.99
$\bar{w}$	3	0	548.20	20.92
T_{Max}	6	1	27.57	10.31
T_{mat}	10	4	7.32	2.49
T [°C]	1	—	26.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1845	0.0554
F_{msm}	19	—	0.0759	0.0221
F_{lim}	19	—	0.1138	0.0331
F_{crash}	19	—	0.1518	0.0442


Natural Mortality Estimator Values & Mgmt Reference Point Spread

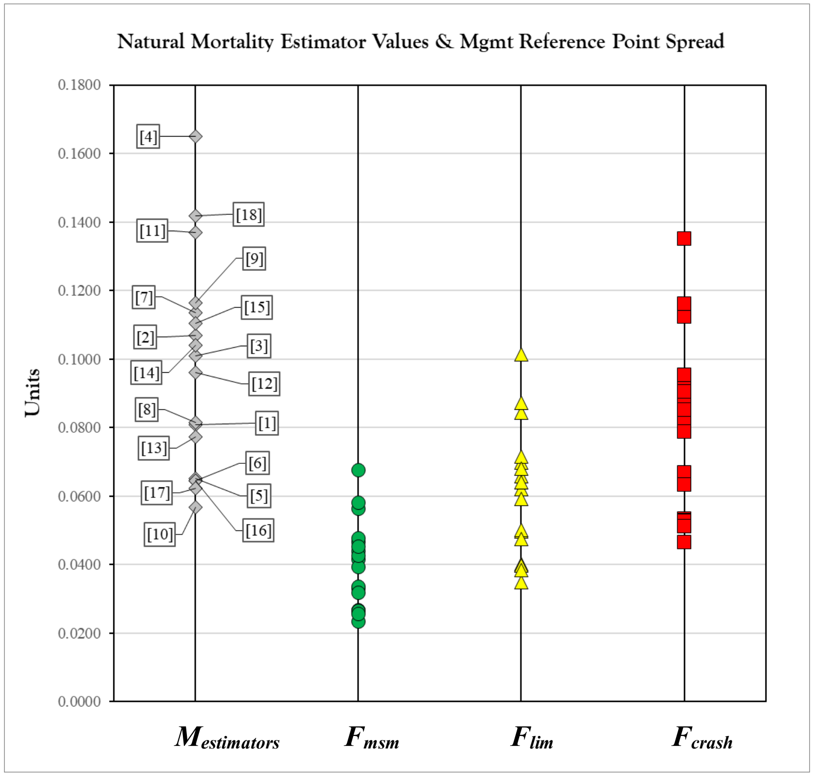
Figures A2–5b. *Galeocerdo cuvier* (Tiger Shark).



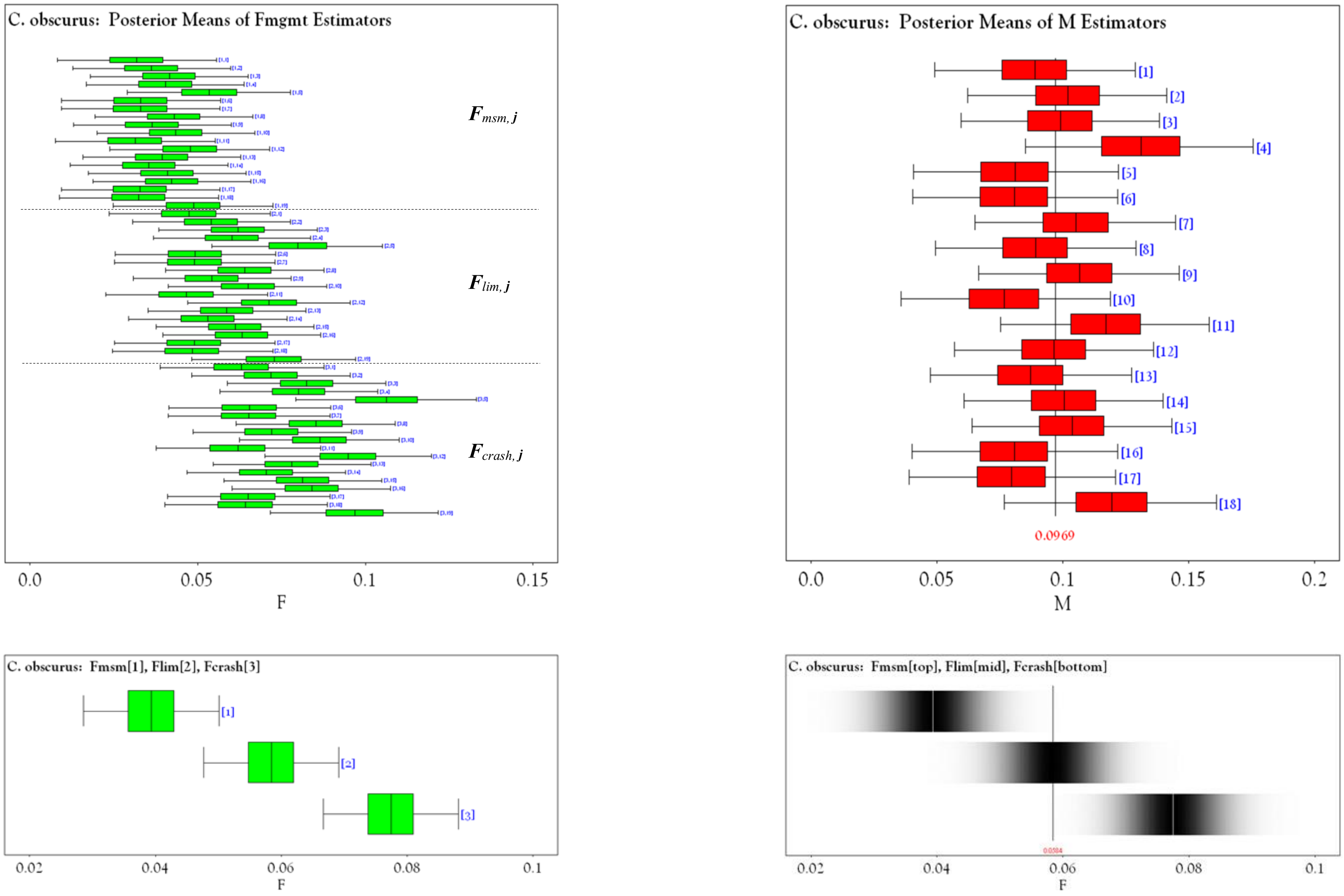
Figures A2–6a. *C. obscurus* (Dusky Shark).



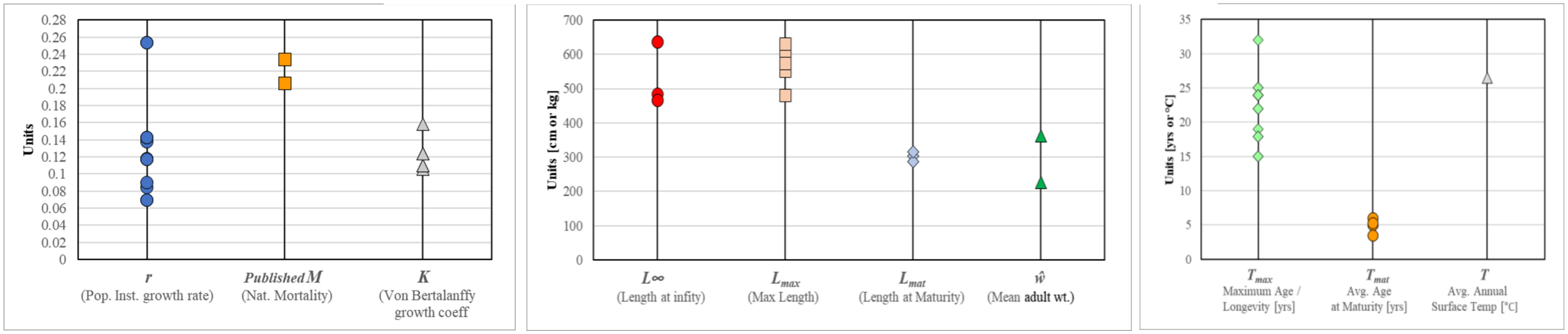
	n_{Total}	n_{Female}	μ	σ_{FW}
r	5	0	0.0487	0.0227
M_{lit}	4	0	0.0808	0.0236
K	6	2	0.0430	0.0059
L_∞	5	0	413.57	10.18
L_{Max}	7	2	357.03	20.32
L_{mat}	3	3	281.29	2.10
$\bar{w}$	2	0	274.01	13.04
T_{Max}	6	4	40.61	4.97
T_{mat}	7	4	19.81	1.37
T [°C]	1	—	26.50	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.0969	0.0307
F_{msm}	19	—	0.0389	0.0127
F_{lim}	19	—	0.0584	0.0191
F_{crash}	19	—	0.0778	0.0255



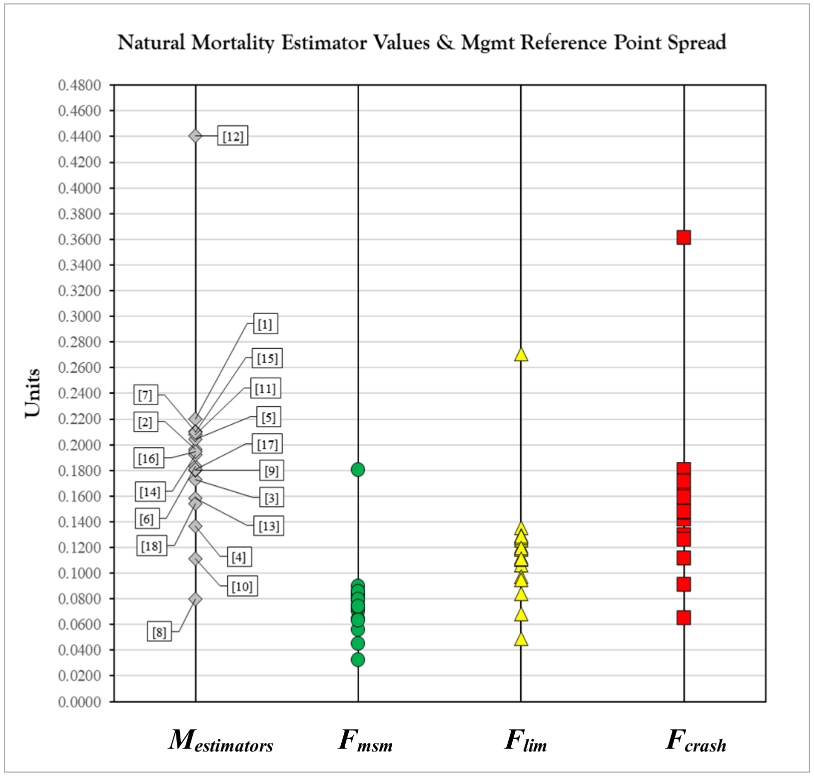
Figures A2–6b. *C. obscurus* (Dusky Shark).



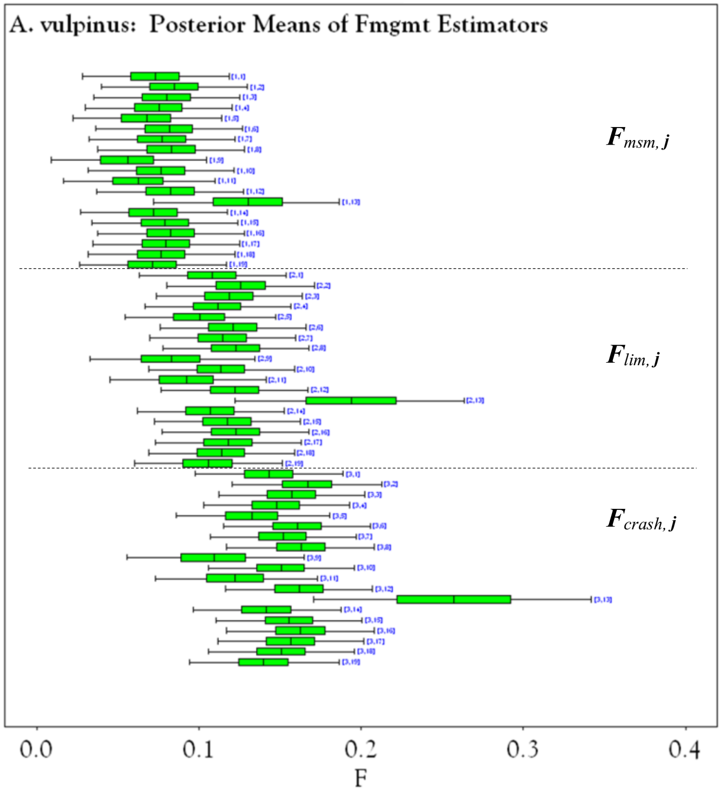
Figures A2–7a. *A. vulpinus* (Common Thresher).

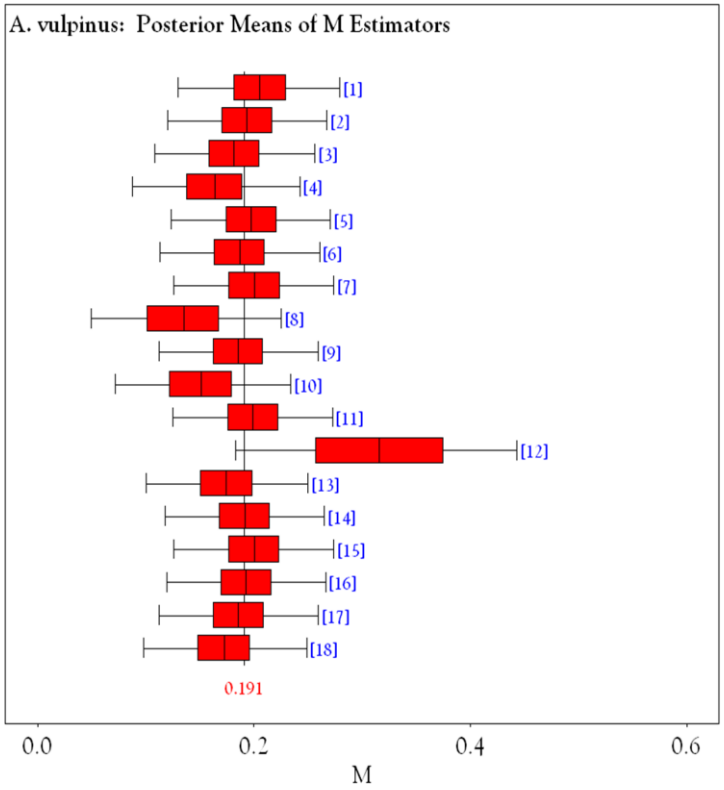


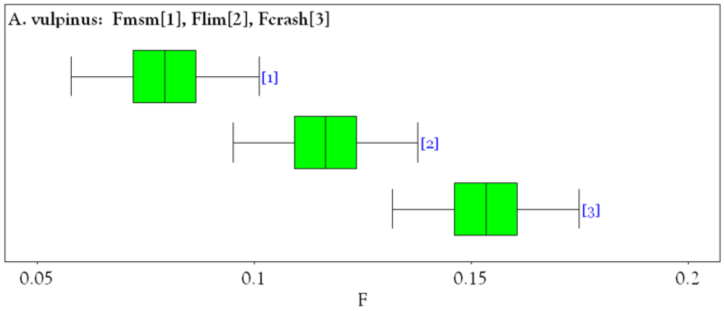
	n_{Total}	n_{Female}	μ	σ_{FW}
r	11	1	0.1329	0.0623
M_{lit}	2	0	0.2201	0.0197
K	4	2	0.1220	0.0192
$L\infty$	3	2	536.96	90.71
L_{Max}	6	3	560.73	52.88
L_{mat}	3	3	301.83	12.33
$\bar{w}$	2	0	294.24	95.65
T_{Max}	9	5	21.92	4.59
T_{mat}	6	3	4.96	0.91
T [°C]	1	—	26.50	—
			$E[\widehat{\mu}]$	$E[\widehat{\sigma}^2]$
M_{est}	18	—	0.1908	0.0724
F_{msm}	19	—	0.0776	0.0290
F_{lim}	19	—	0.1164	0.0434
F_{crash}	19	—	0.1552	0.0579

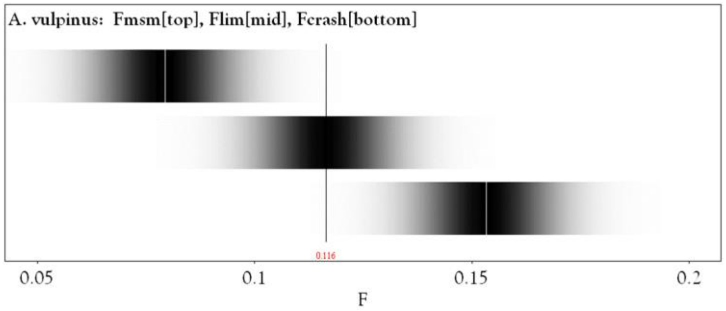


Figures A2–7b. *vulpinus* (Common Thresher).

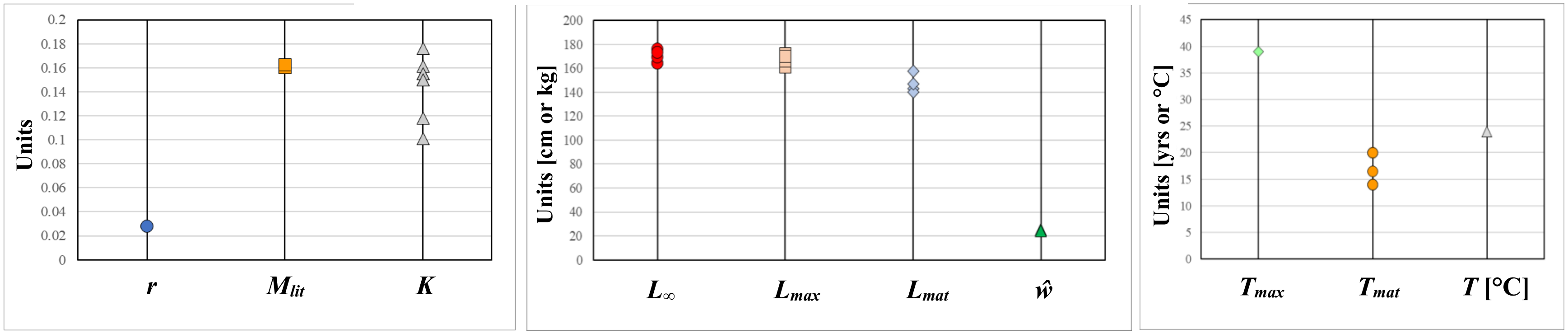




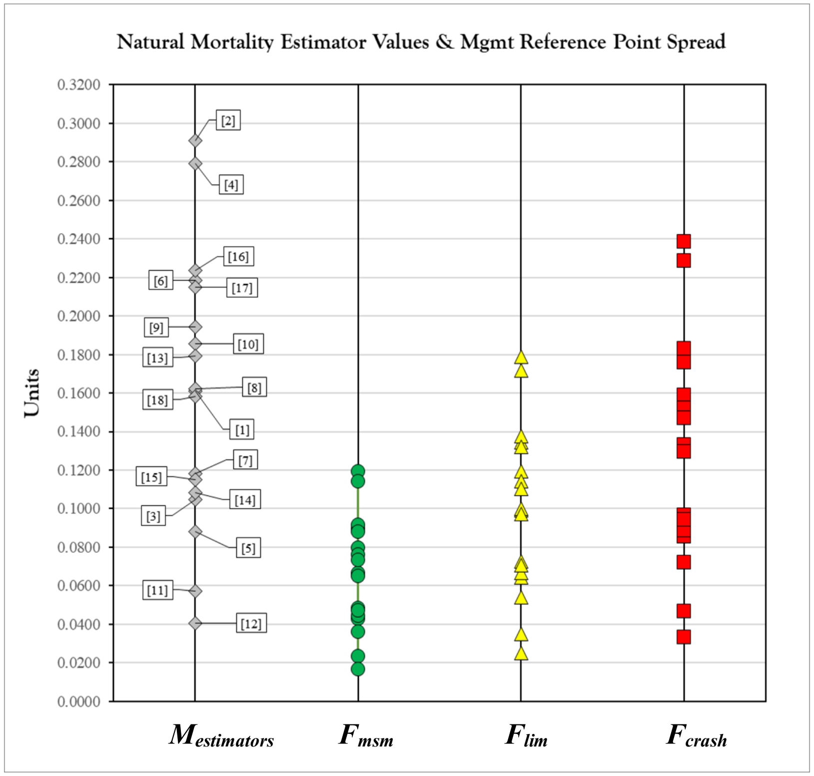




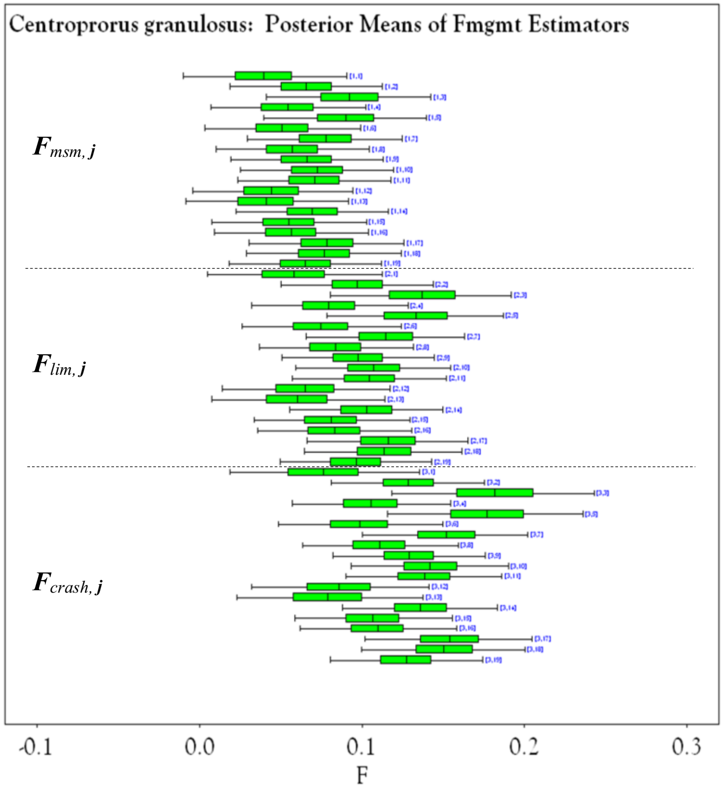
Figures A2–8a. *Centrophorus granulosus* (Gulper Shark).

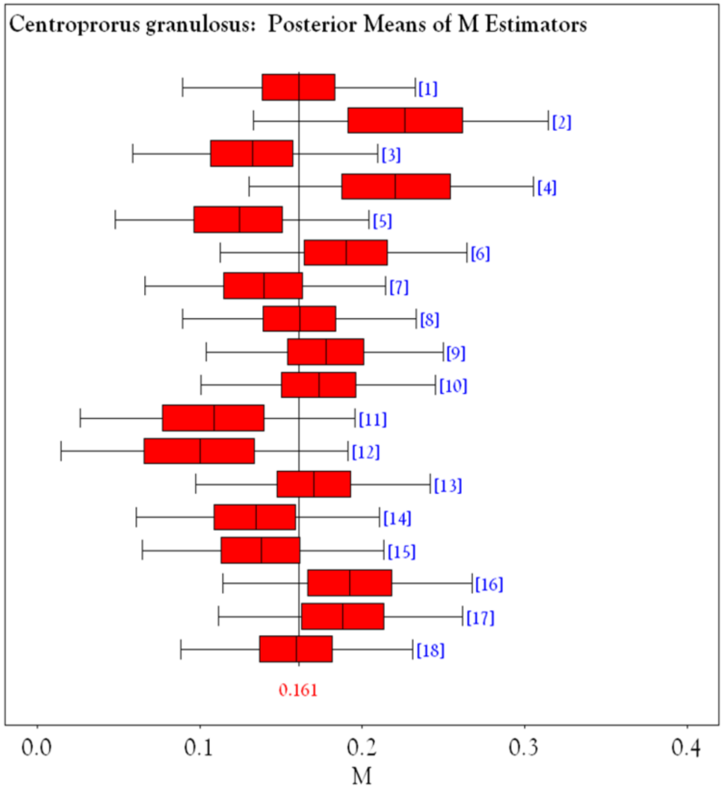


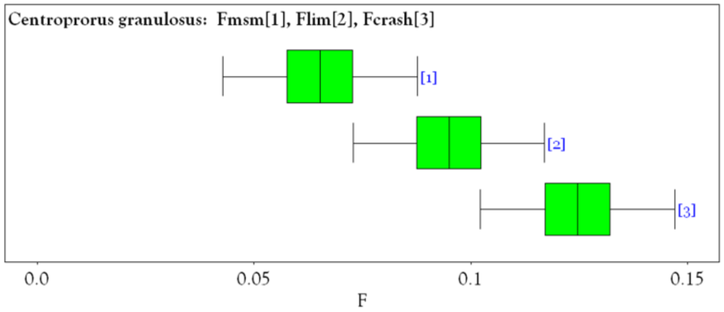
	n_{Total}	n_{Female}	μ	σ_{FW}
r	1	0	0.0278	N/A
M_{lit}	2	0	0.1611	0.0015
K	6	2	0.1458	0.0243
$L\infty$	5	0	169.46	5.24
L_{Max}	5	0	166.10	5.20
L_{mat}	4	4	146.88	7.07
$\bar{w}$	2	0	25.03	0.70
T_{Max}	1	0	39.00	N/A
T_{mat}	3	2	16.90	3.01
T [°C]	1	—	24.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1611	0.0701
F_{msm}	19	—	0.0633	0.0304
F_{lim}	19	—	0.0950	0.0456
F_{crash}	19	—	0.1266	0.0608

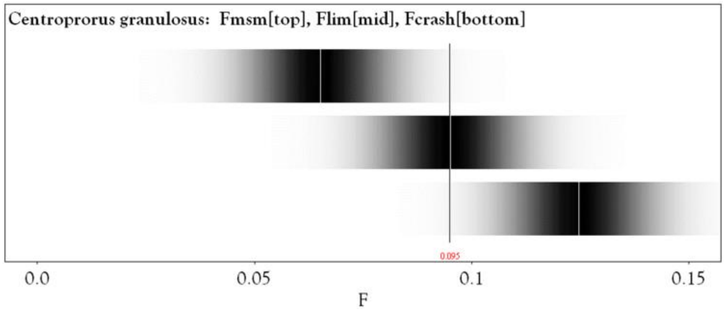

Natural Mortality Estimator Values & Mgmt Reference Point Spread

Figures A2–8b. *Centrophorus granulosus* (Gulper Shark).



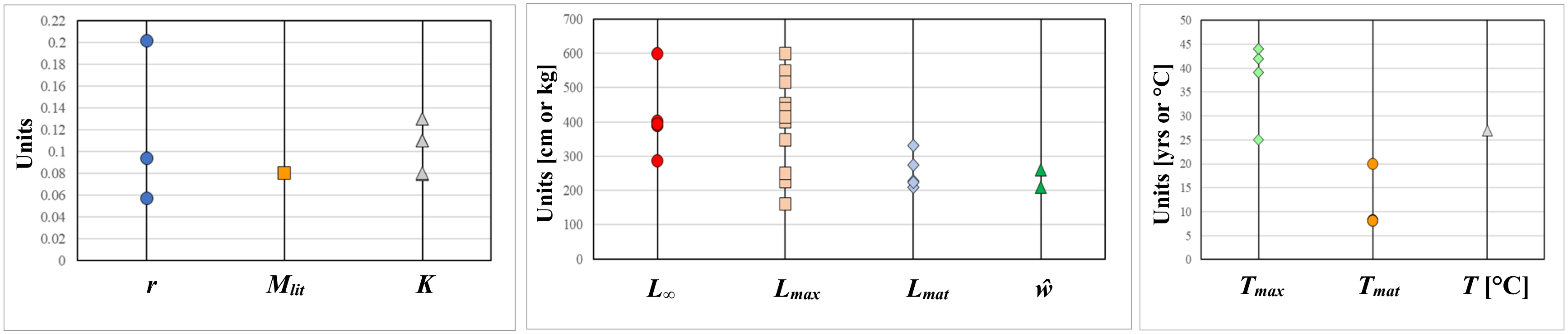




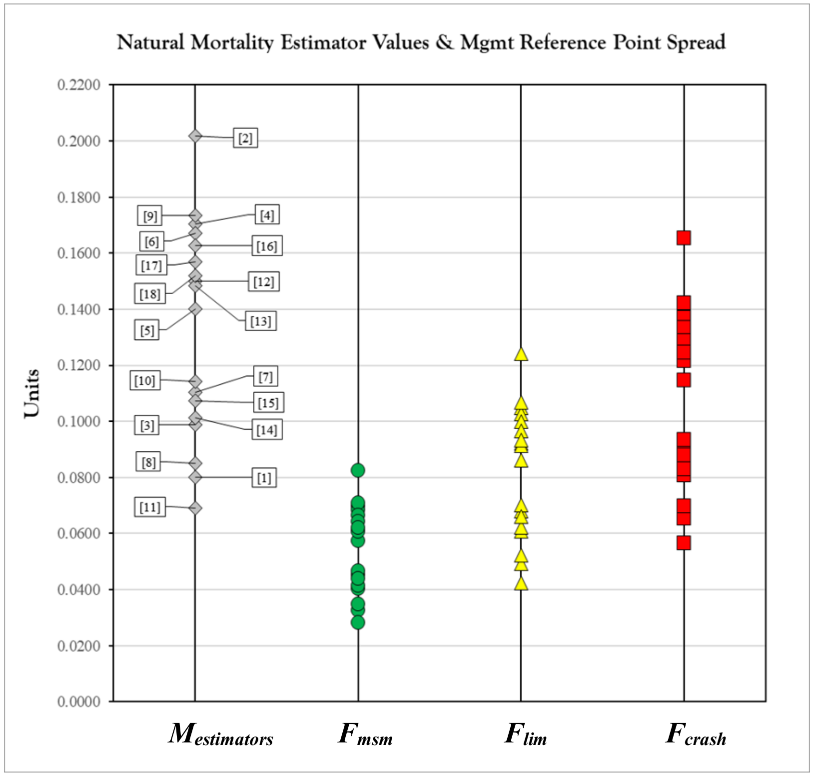


Figures A2–10a. *S. mokarran* (Great Hammerhead).

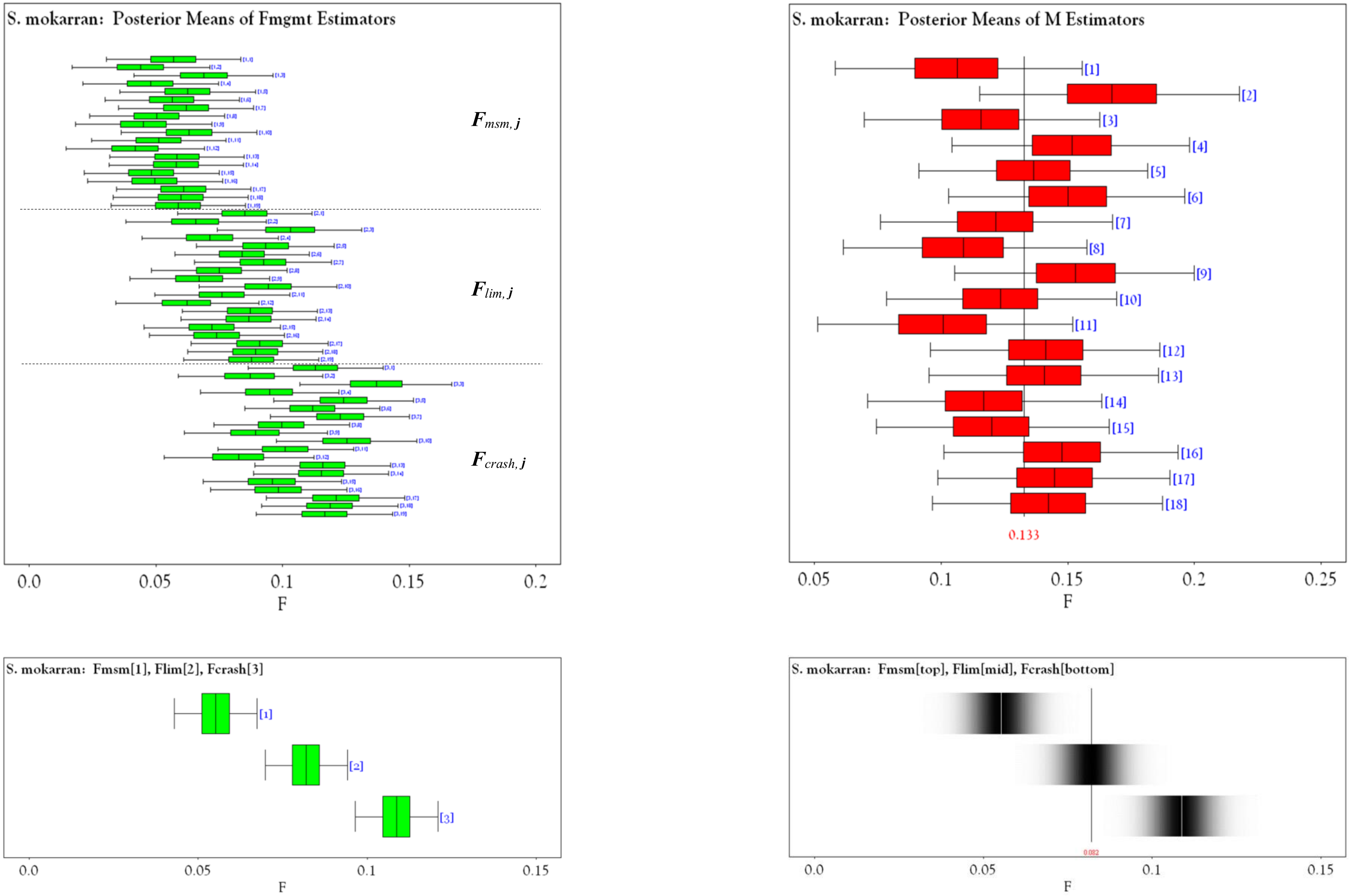
[Skipped nos. in this section are intentional, numbering scheme corresponds w/ study designated spp. nos. outlined in Table17]



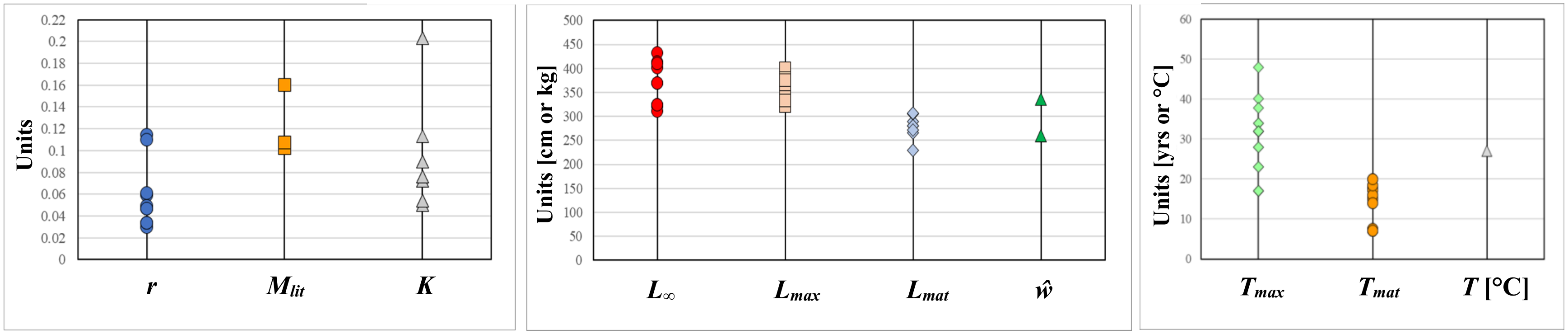
	n_{Total}	n_{Female}	μ	σ_{FW}
r	3	0	0.1174	0.0755
M_{lit}	1	0	0.0800	N/A
K	5	3	0.1074	0.0193
$L\infty$	5	2	408.23	93.59
L_{Max}	13	6	421.27	115.95
L_{mat}	5	5	253.68	47.06
$\bar{w}$	2	0	235.60	35.59
T_{Max}	4	3	39.31	6.62
T_{mat}	3	2	10.52	5.30
T [°C]	1	—	27.00	—
			$E[\widehat{\mu}]$	$E[\widehat{\sigma}^2]$
M_{est}	18	—	0.1327	0.0377
F_{msm}	19	—	0.0546	0.0151
F_{lim}	19	—	0.0820	0.0226
F_{crash}	19	—	0.1093	0.0301



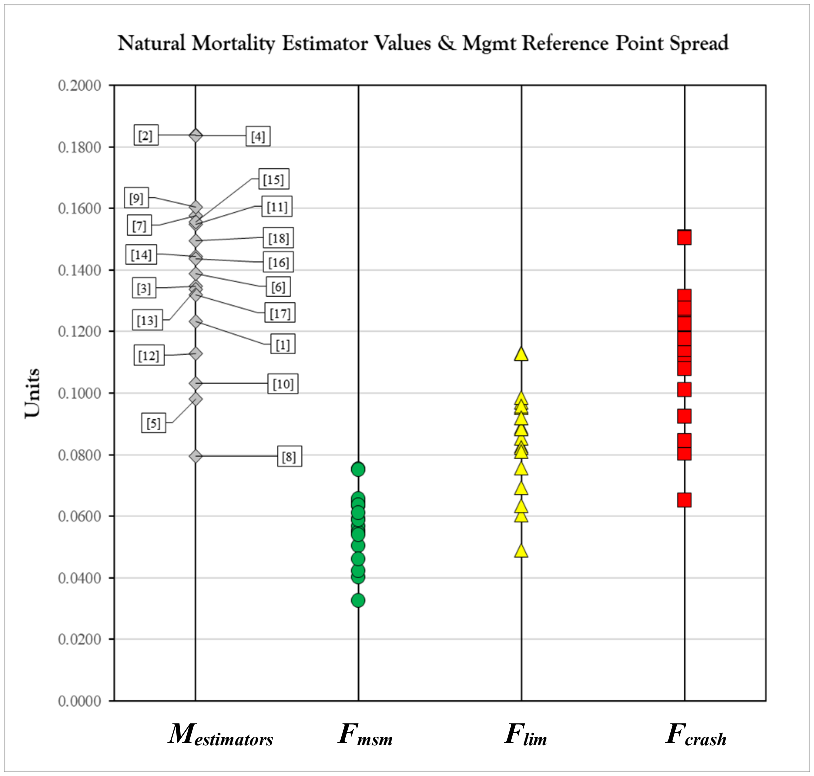
Figures A2–10b. *S. mokarran* (Great Hammerhead).



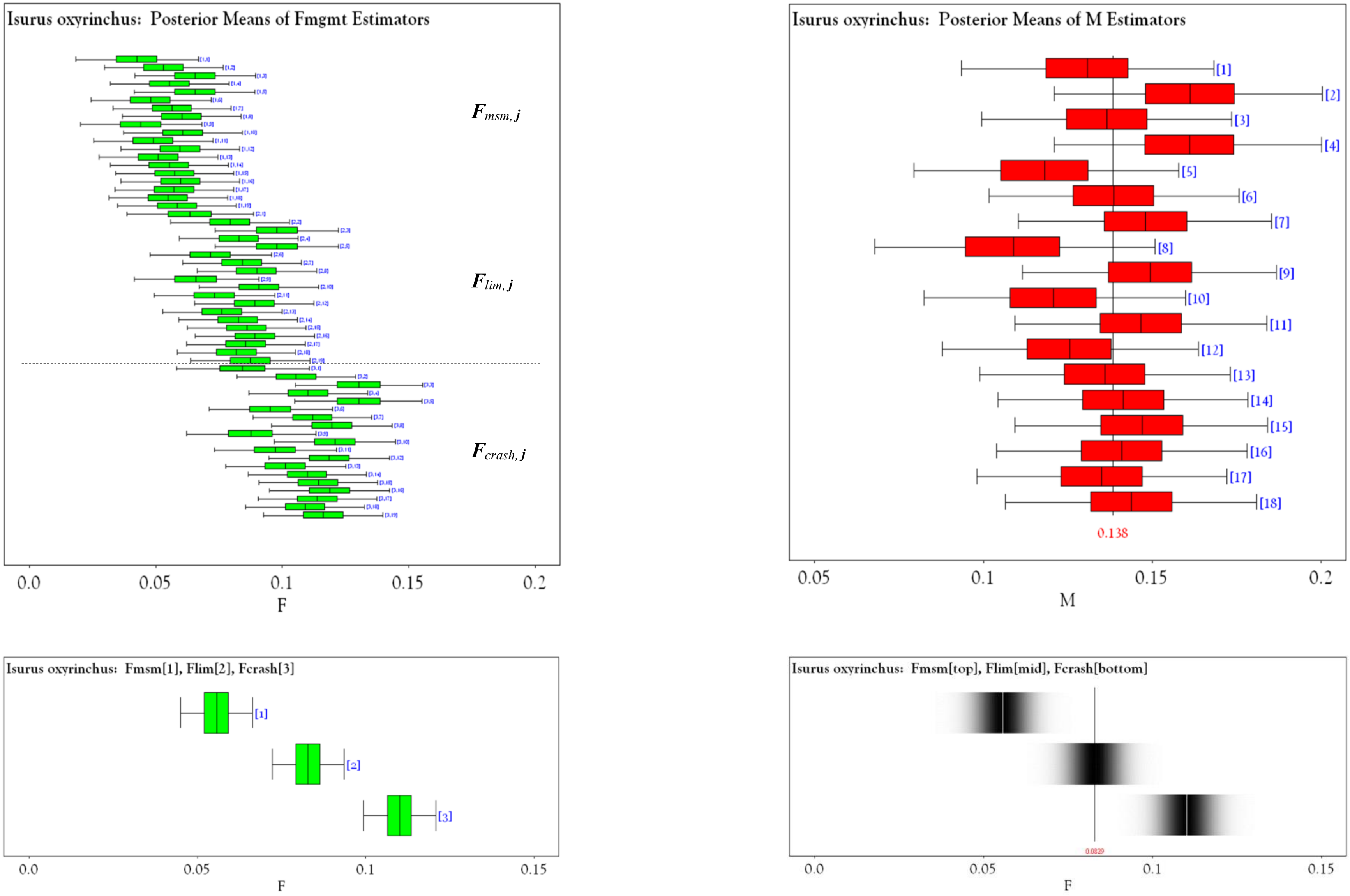
Figures A2–11a. *Isurus oxyrinchus* (Shortfin Mako).



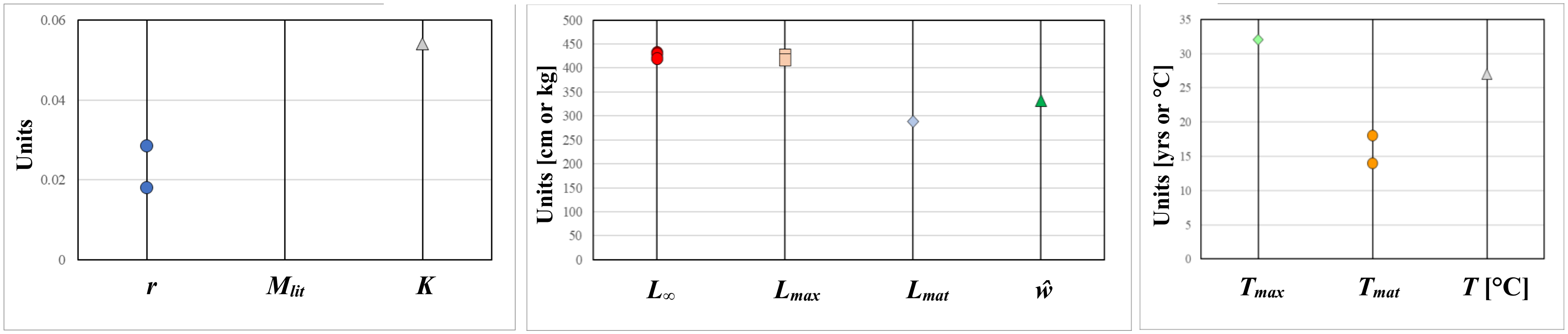
	n_{Total}	n_{Female}	μ	σ_{FW}
r	8	2	0.0586	0.0301
M_{lit}	3	0	0.1232	0.0319
K	9	4	0.0925	0.0523
L_∞	8	2	368.08	45.26
L_{Max}	9	7	358.69	24.05
L_{mat}	8	8	278.73	23.73
$\bar{w}$	2	0	298.17	53.09
T_{Max}	12	8	29.20	8.32
T_{mat}	14	10	13.41	5.21
T [°C]	1	—	27.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1383	0.0277
F_{msm}	19	—	0.0553	0.0127
F_{lim}	19	—	0.0829	0.0190
F_{crash}	19	—	0.1105	0.0254



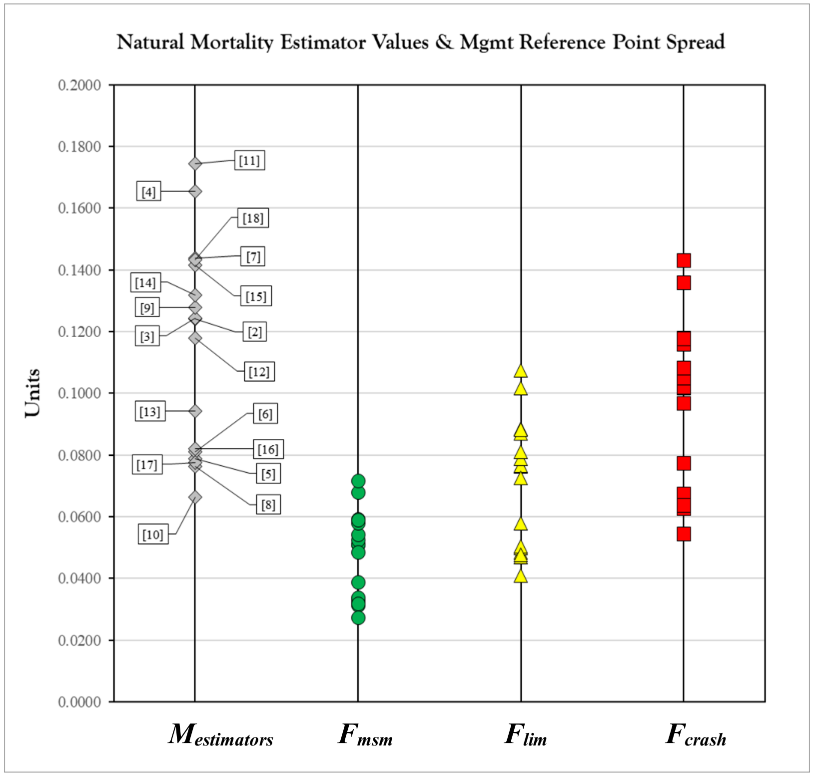
Figures A2–11b. *Isurus oxyrinchus* (Shortfin Mako).



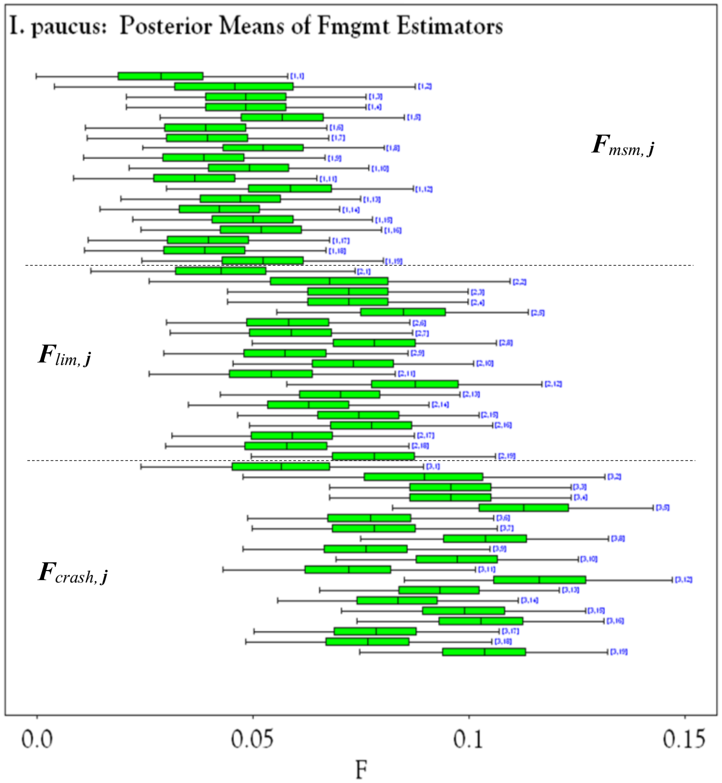
Figures A2–12a. *Isurus paucus* (Longfin Mako).

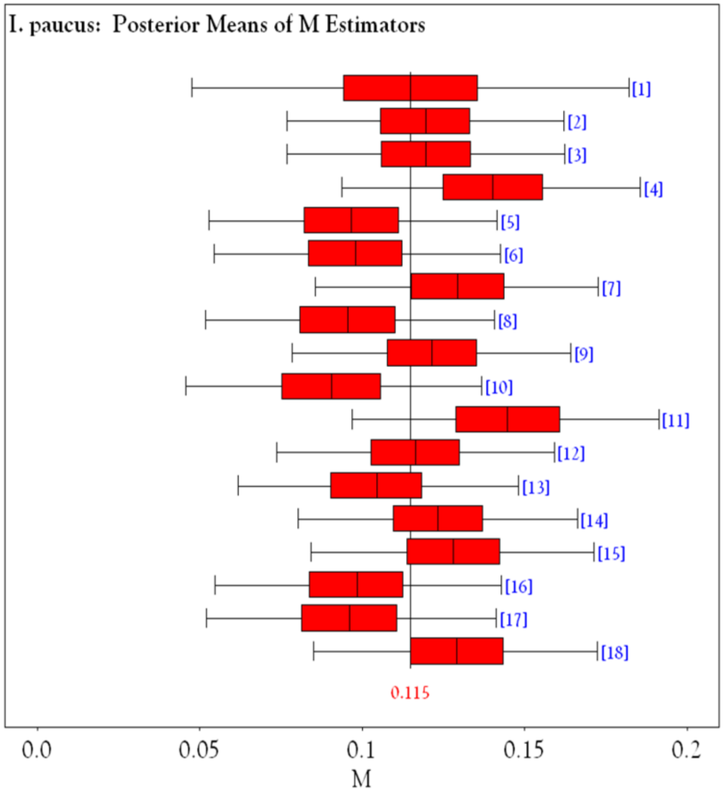


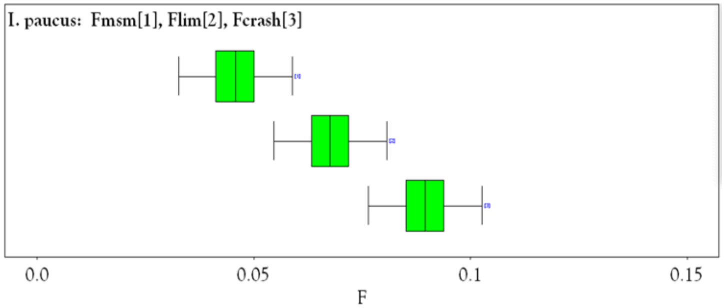
	n_{Total}	n_{Female}	μ	σ_{FW}
r	2	0	0.0233	0.0075
M_{lit}	0	0	N/A	N/A
K	1	0	0.0540	N/A
$L\infty$	3	1	424.91	6.64
L_{Max}	2	1	420.33	5.77
L_{mat}	1	0	288.50	N/A
$\bar{w}$	1	0	332.56	N/A
T_{Max}	1	0	32.00	N/A
T_{mat}	2	0	16.00	2.83
T [°C]	1	—	27.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	17	—	0.1148	0.0338
F_{msm}	18	—	0.0451	0.0158
F_{lim}	18	—	0.0676	0.0238
F_{crash}	18	—	0.0902	0.0317

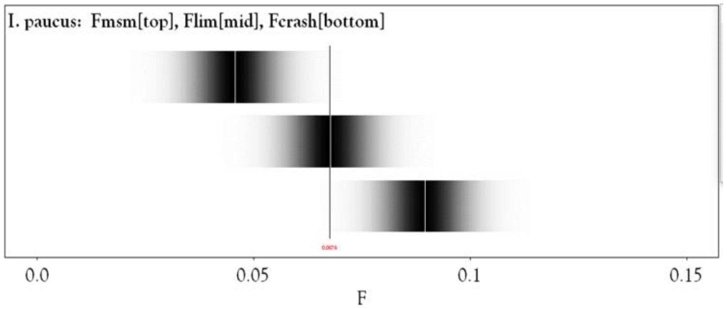


Figures A2–12b. *Isurus paucus* (Longfin Mako).

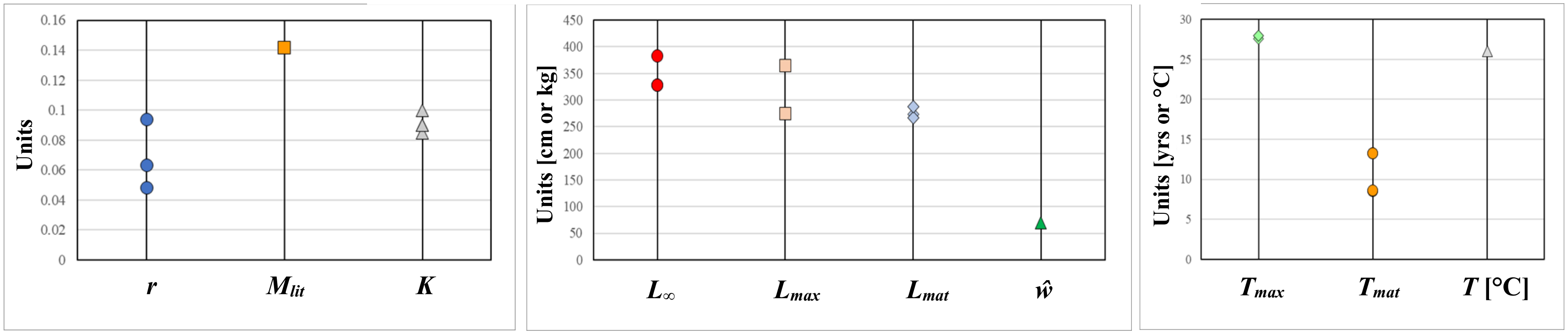




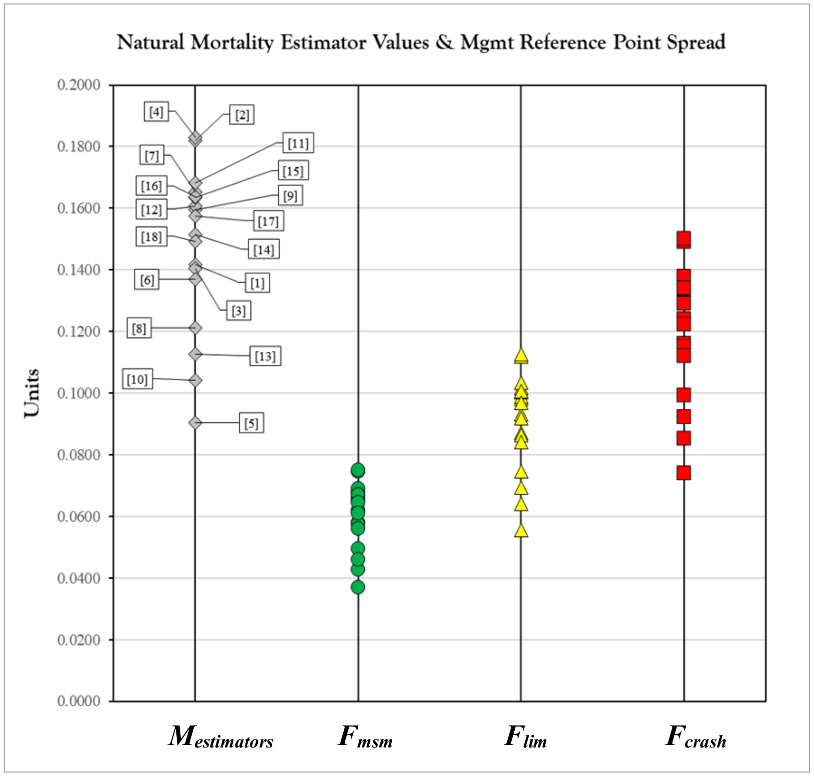




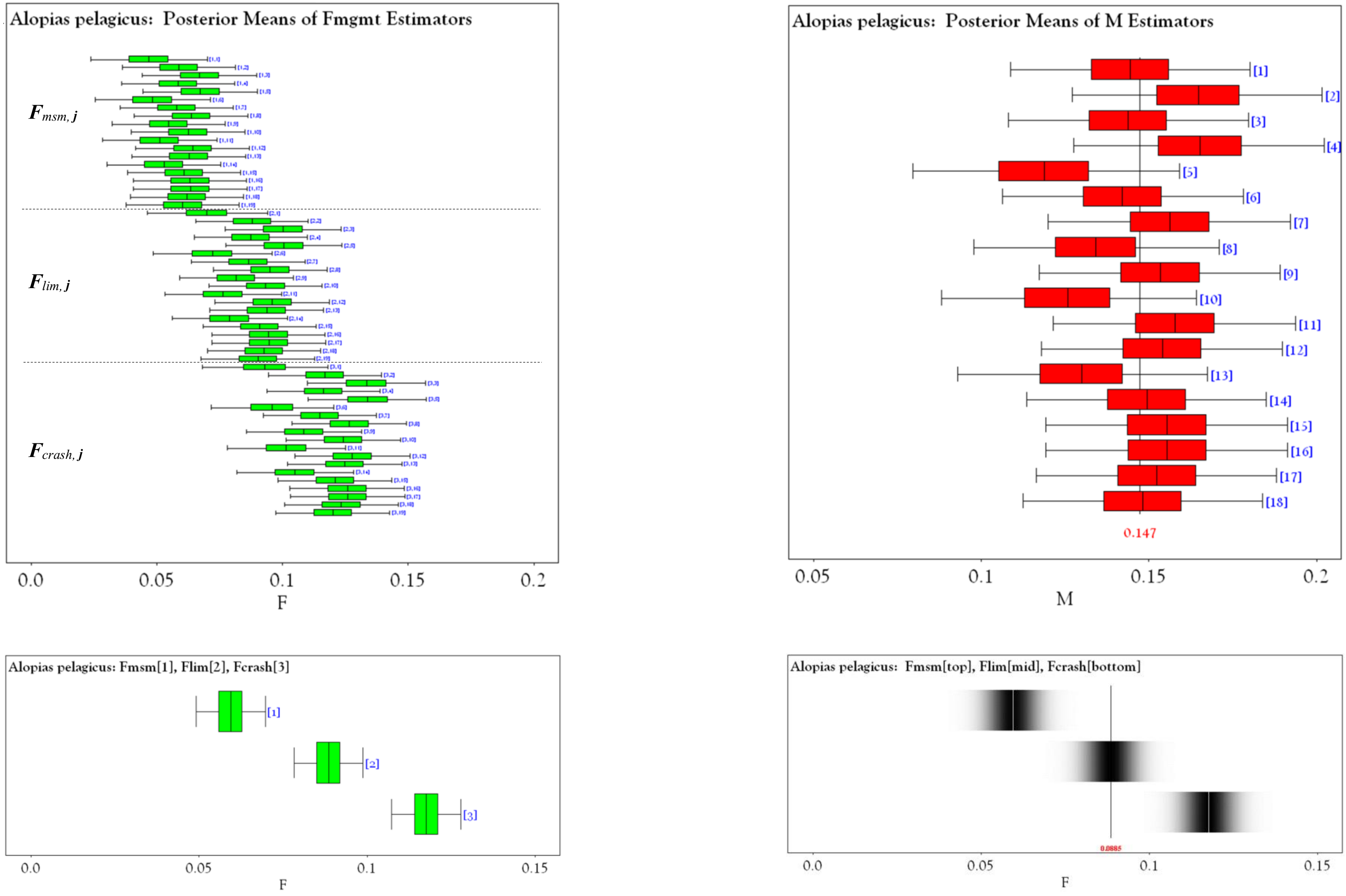
Figures A2–13a. *Alopias pelagicus* (Pelagic Thresher).



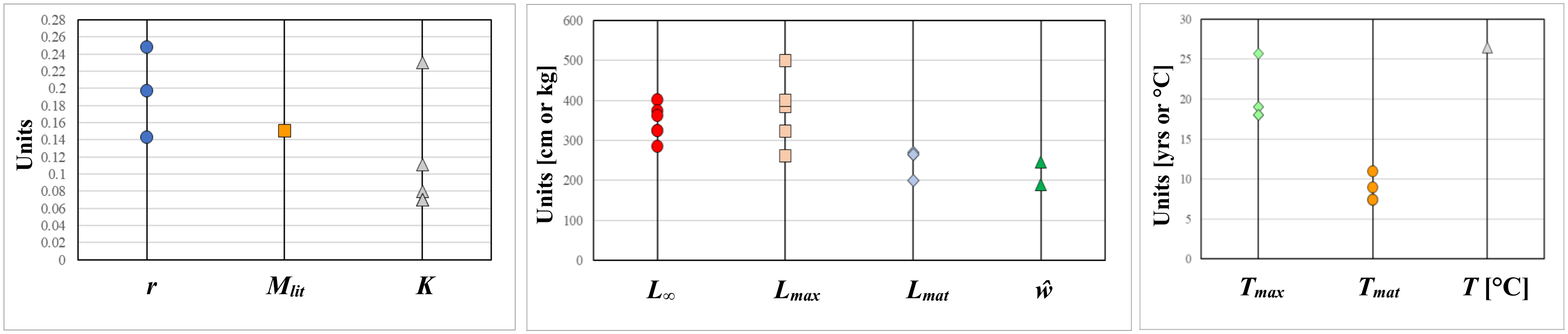
	n_{Total}	n_{Female}	μ	σ_{FW}
r	3	0	0.0683	0.0231
M_{lit}	1	0	0.1416	N/A
K	3	1	0.0913	0.0063
$L\infty$	2	1	346.38	31.66
L_{Max}	2	0	320.09	63.77
L_{mat}	3	2	276.04	10.34
$\bar{w}$	1	0	69.03	N/A
T_{Max}	2	1	27.86	0.25
T_{mat}	3	1	10.90	2.71
T [°C]	1	—	26.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1473	0.0259
F_{msm}	19	—	0.0590	0.0120
F_{lim}	19	—	0.0885	0.0179
F_{crash}	19	—	0.1180	0.0239



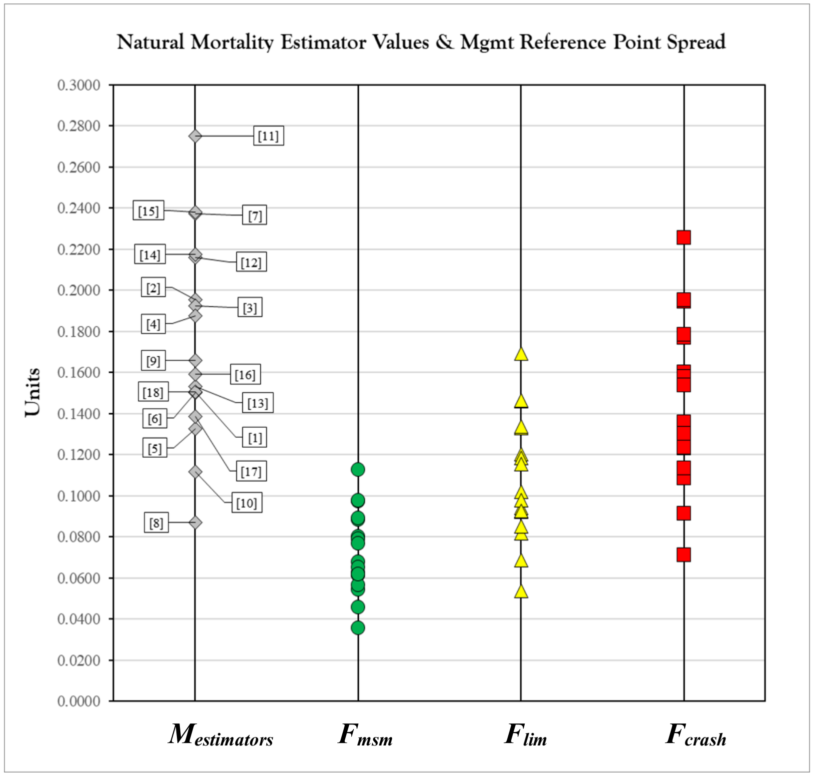
Figures A2–13b. *Alopias pelagicus* (Pelagic Thresher).



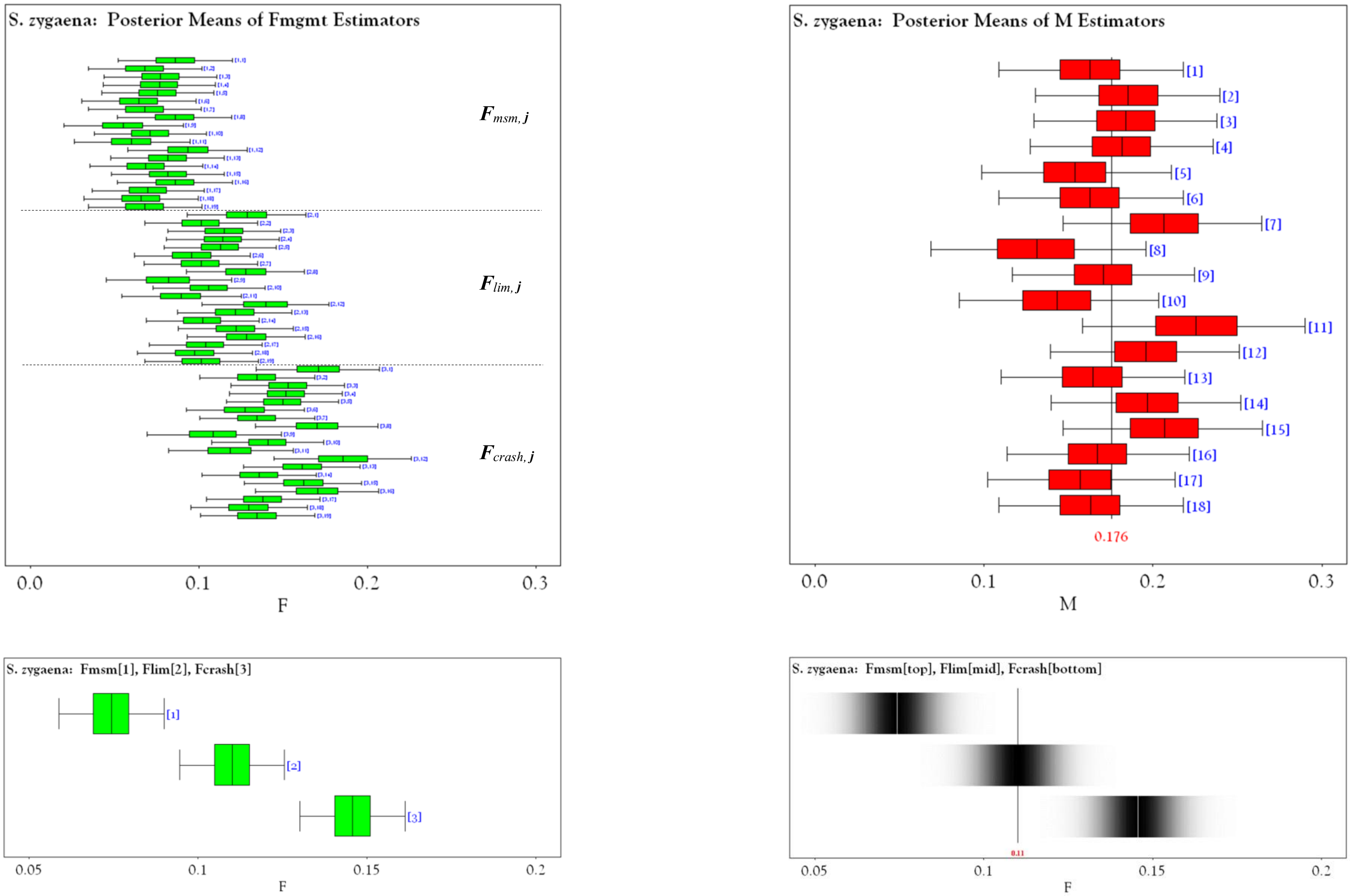
Figures A2–14a. *Sphyrna zygaena* (Smooth Hammerhead).



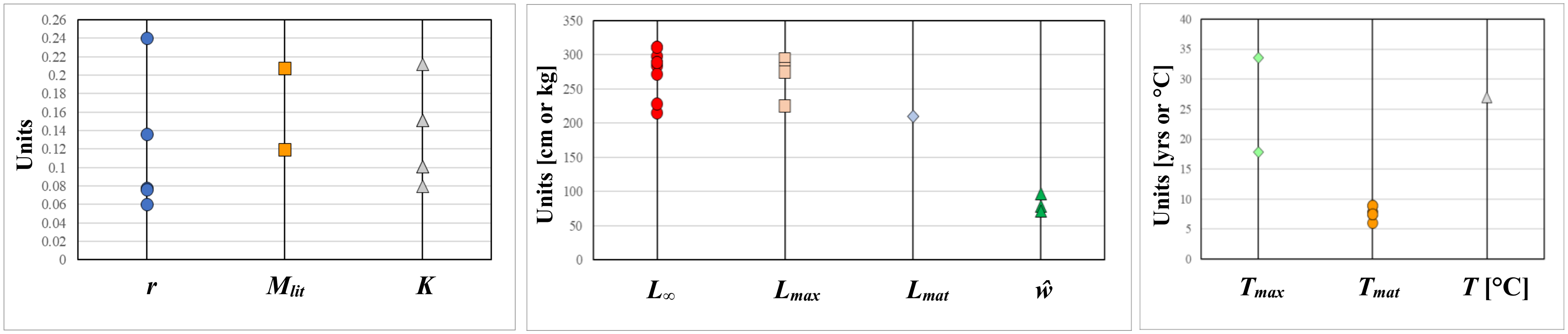
	n_{Total}	n_{Female}	μ	σ_{FW}
r	3	0	0.1961	0.0523
M_{lit}	1	0	0.1504	N/A
K	5	2	0.1001	0.0592
$L\infty$	5	1	345.53	42.37
L_{Max}	6	2	364.51	79.97
L_{mat}	4	4	250.00	30.94
$\bar{w}$	2	0	217.84	39.53
T_{Max}	4	3	19.39	2.84
T_{mat}	3	1	8.70	1.71
T [°C]	1	—	26.50	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1755	0.0484
F_{msm}	19	—	0.0733	0.0202
F_{lim}	19	—	0.1100	0.0303
F_{crash}	19	—	0.1467	0.0404



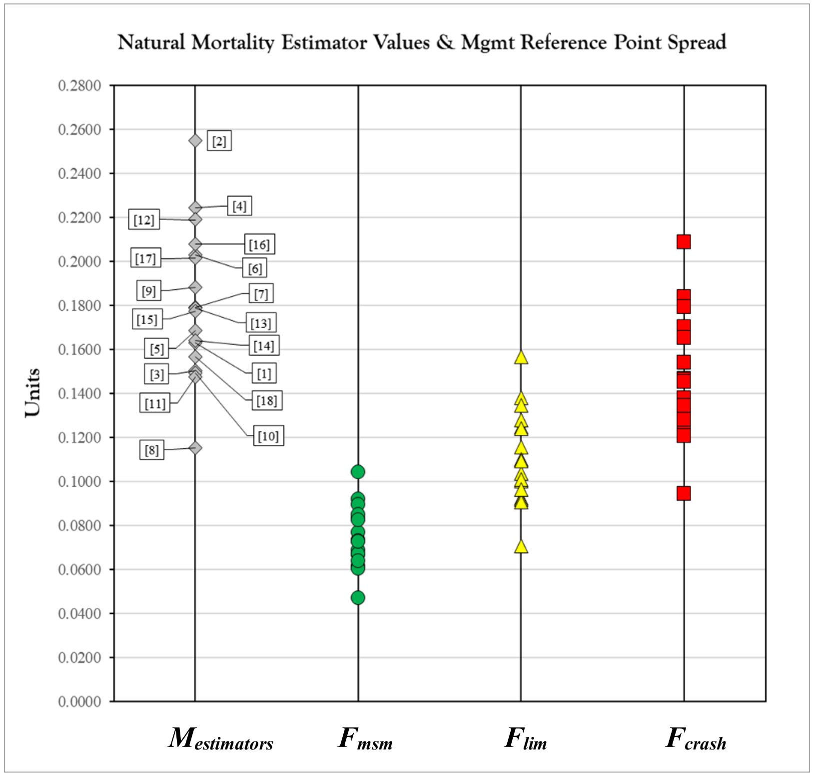
Figures A2–14b. *Sphyrna zygaena* (Smooth Hammerhead).



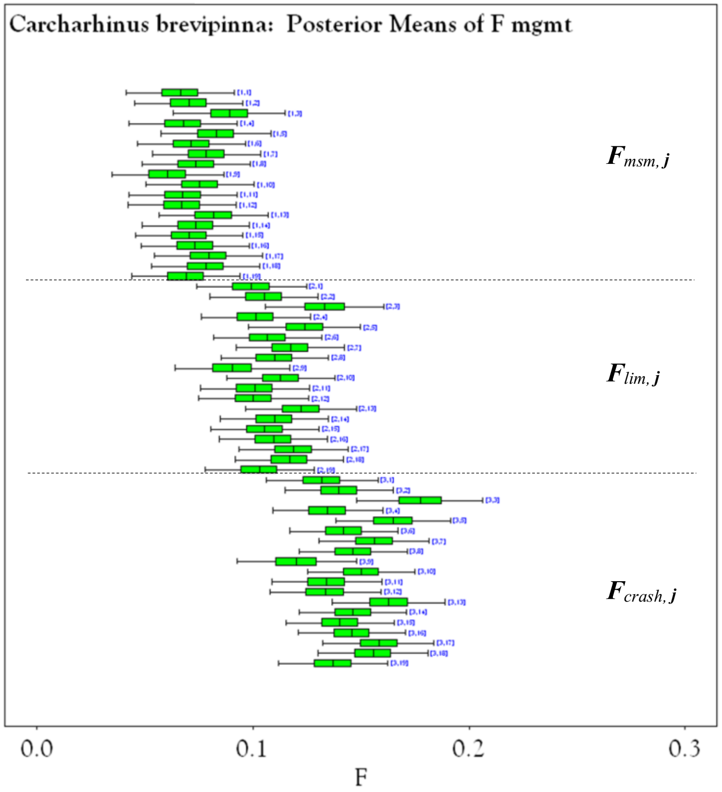
Figures A2–16a. *Carcharhinus brevipinna* (Spinner Shark).

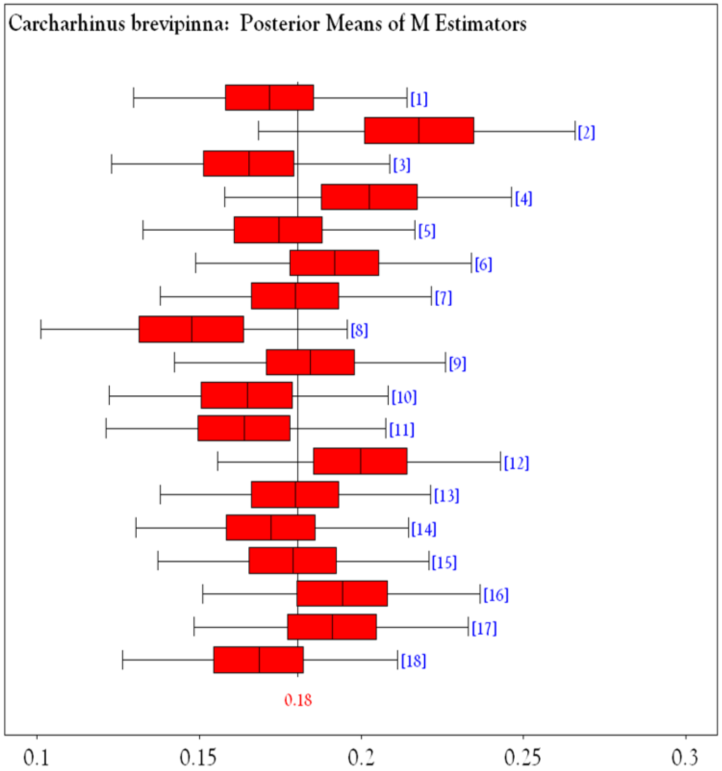


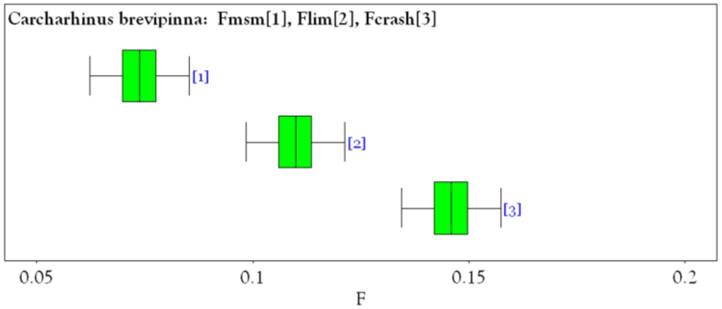
	n_{Total}	n_{Female}	μ	σ_{FW}
r	5	0	0.1178	0.0741
M_{lit}	2	0	0.1631	0.0621
K	5	2	0.1353	0.0448
$L\infty$	8	2	278.00	32.30
L_{Max}	5	0	259.54	32.52
L_{mat}	1	1	210.00	0.00
$\bar{w}$	5	0	88.49	17.35
T_{Max}	2	0	25.73	11.14
T_{mat}	6	3	7.75	0.86
T [°C]	1	—	27.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1805	0.0337
F_{msm}	19	—	0.0732	0.0138
F_{lim}	19	—	0.1098	0.0208
F_{crash}	19	—	0.1464	0.0277

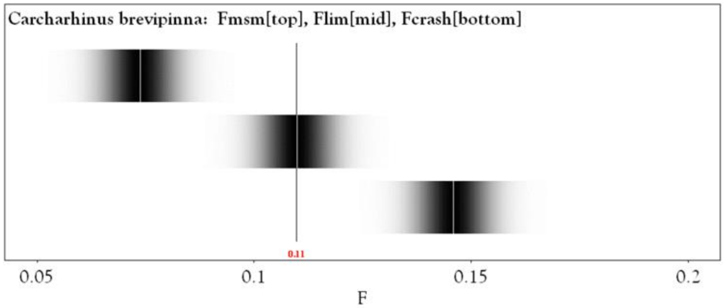


Figures A2–16b. *Carcharhinus brevipinna* (Spinner Shark).

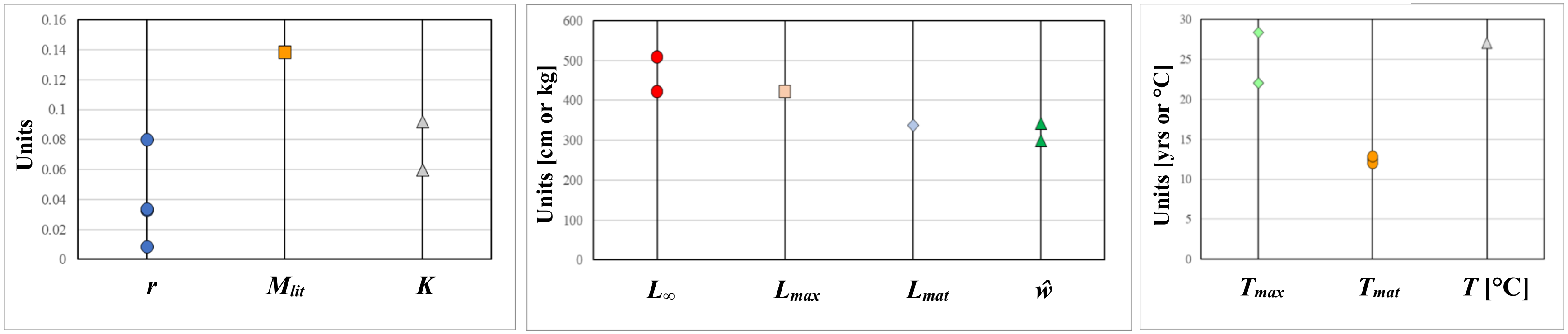




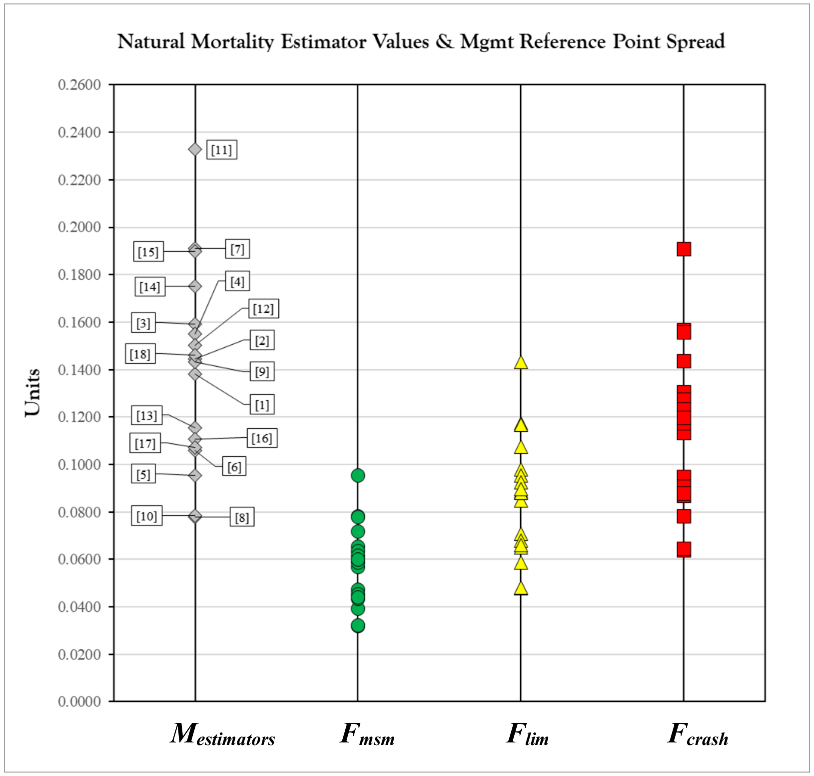




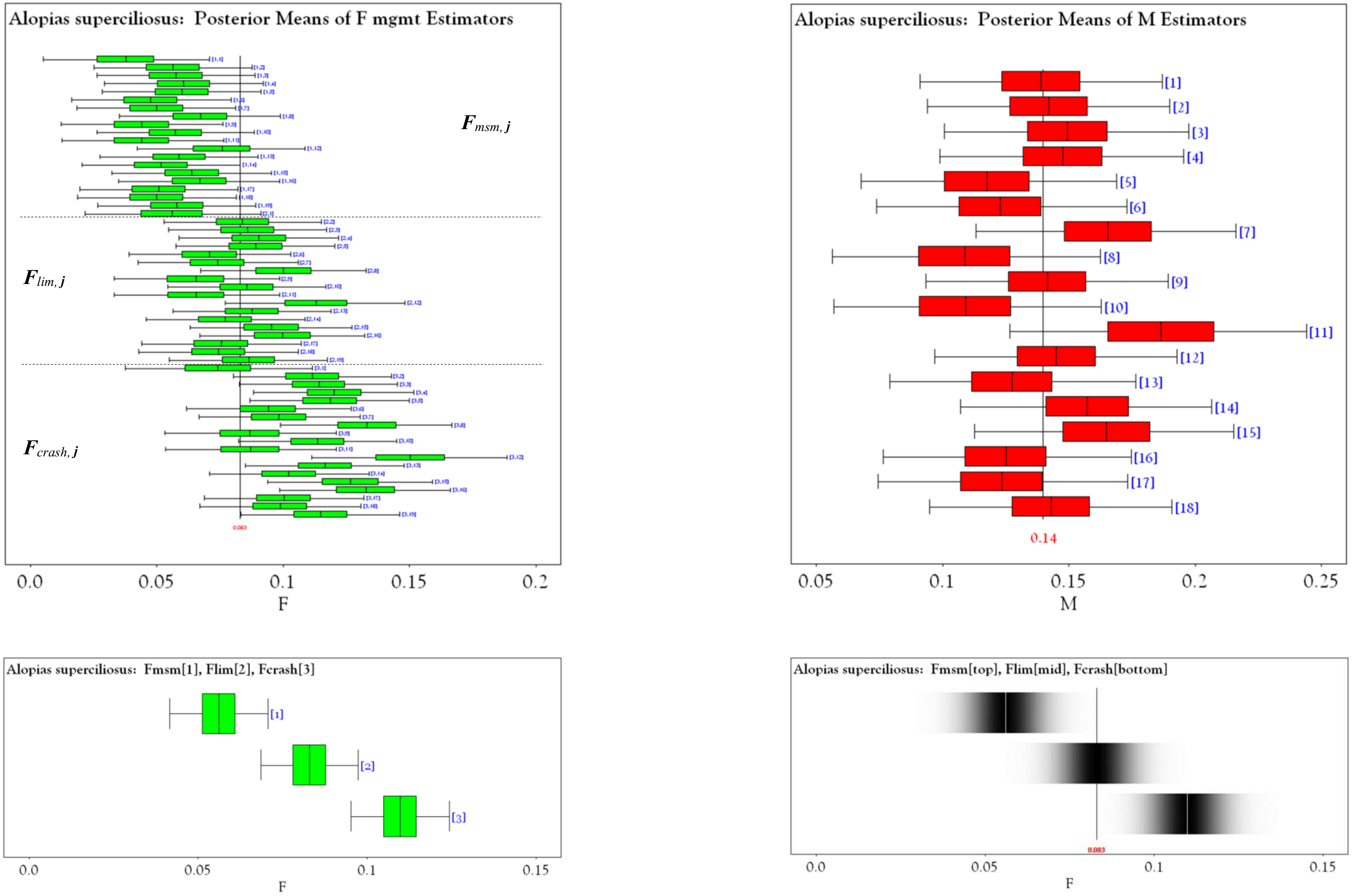
Figures A2–17a. *Alopias superciliosus* (Bigeye Thresher).



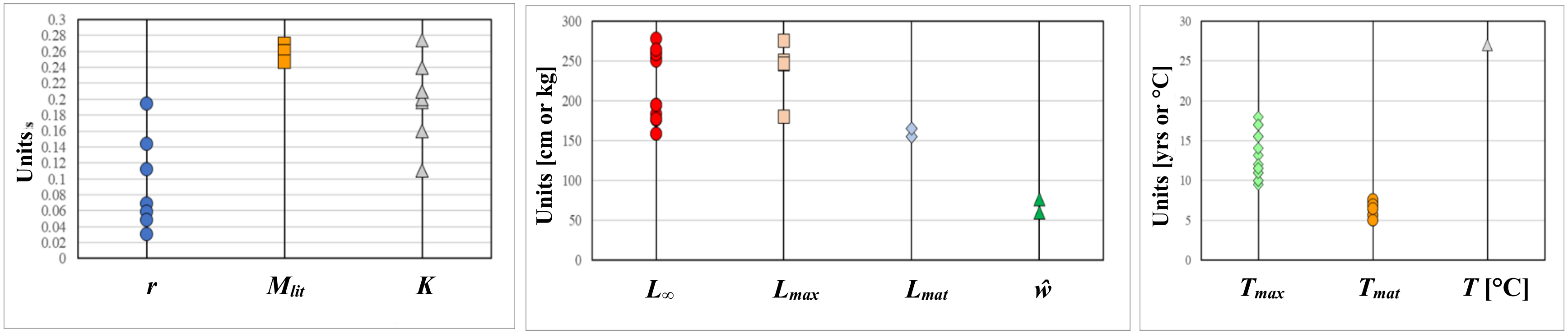
	n_{Total}	n_{Female}	μ	σ_{FW}
r	4	0	0.0386	0.0299
M_{lit}	1	0	0.1382	N/A
K	2	1	0.0707	0.0185
$L\infty$	2	2	465.00	49.65
L_{Max}	1	0	422.00	N/A
L_{mat}	1	0	336.58	N/A
$\bar{w}$	2	0	320.22	30.48
T_{Max}	2	1	24.12	3.67
T_{mat}	3	0	12.45	0.43
T [°C]	1	—	27.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.1398	0.0413
F_{msm}	19	—	0.0553	0.0186
F_{lim}	19	—	0.0830	0.0279
F_{crash}	19	—	0.1106	0.0373



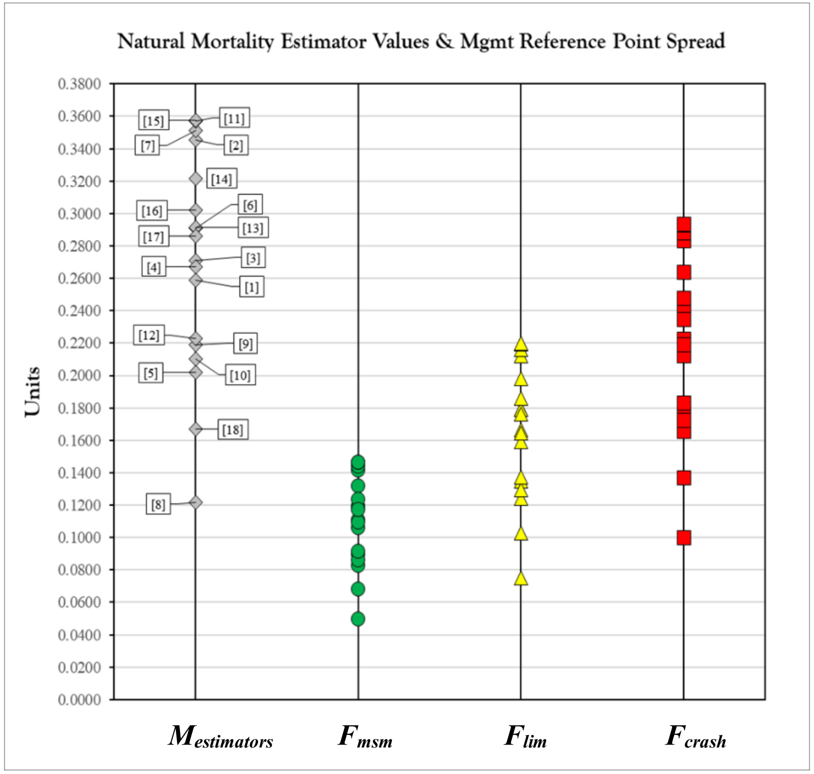
Figures A2–17b. *Alopias superciliosus* (Bigeye Thresher).



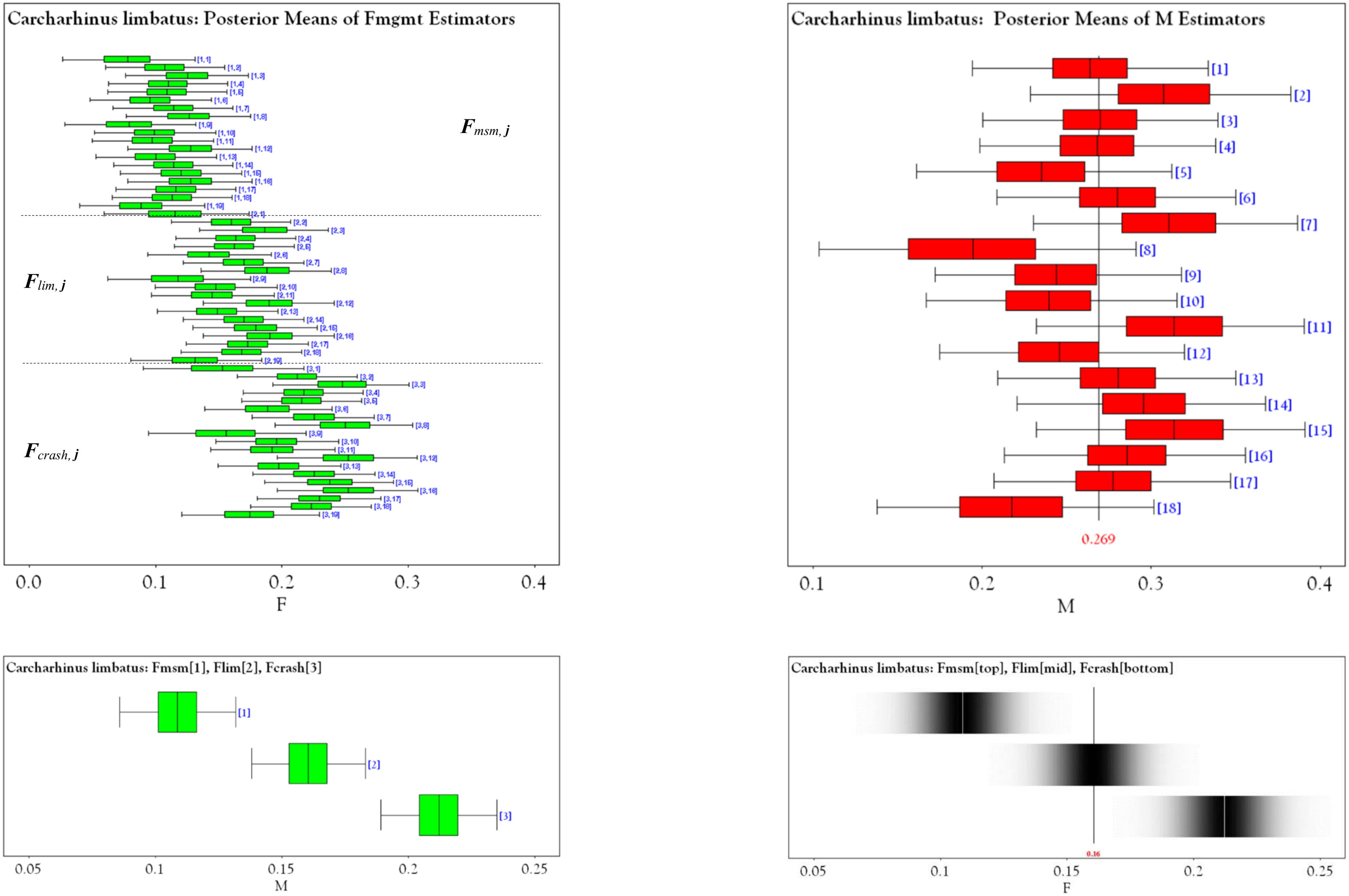
Figures A2–22a. *Carcharhinus limbatus* (Blacktip Shark).



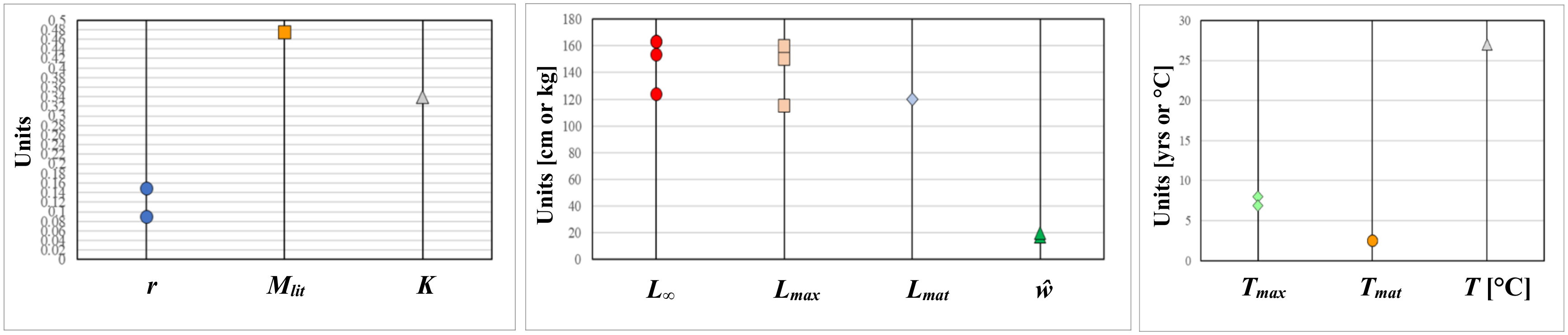
	n_{Total}	n_{Female}	μ	σ_{FW}
r	7	0	0.0941	0.0591
M_{lit}	3	0	0.2590	0.0115
K	8	5	0.1939	0.0482
$L\infty$	12	5	218.01	43.47
L_{Max}	6	0	229.62	39.90
L_{mat}	2	2	160.00	5.77
$\bar{w}$	2	0	68.04	11.51
T_{Max}	10	5	13.11	2.86
T_{mat}	10	8	6.62	0.81
T [°C]	1	—	27.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.2691	0.0678
F_{msm}	19	—	0.1070	0.0307
F_{lim}	19	—	0.1605	0.0460
F_{crash}	19	—	0.2140	0.0613

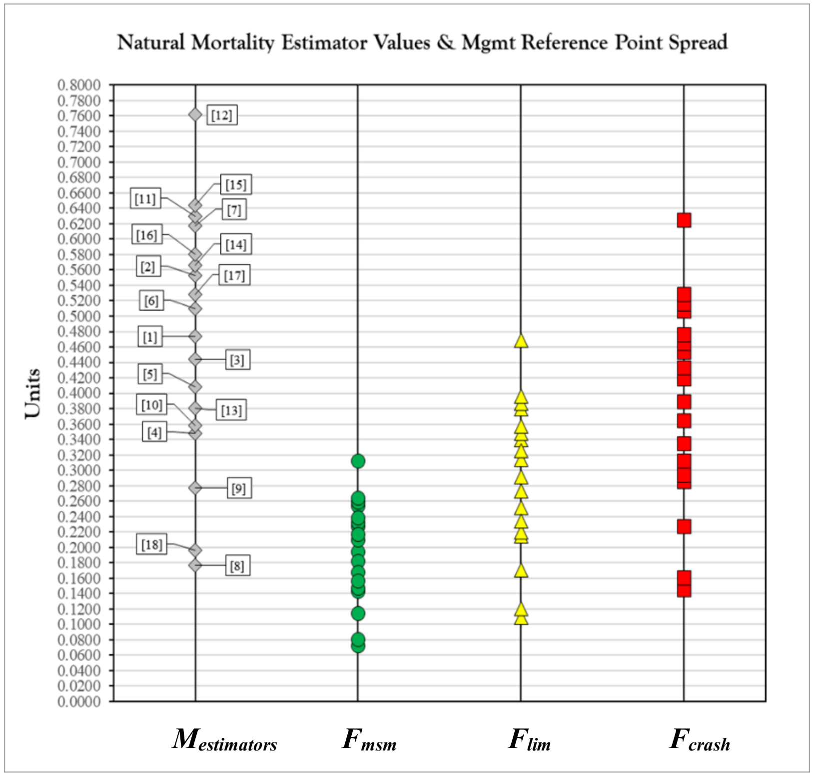


Figures A2–22b. *Carcharhinus limbatus* (Blacktip Shark).



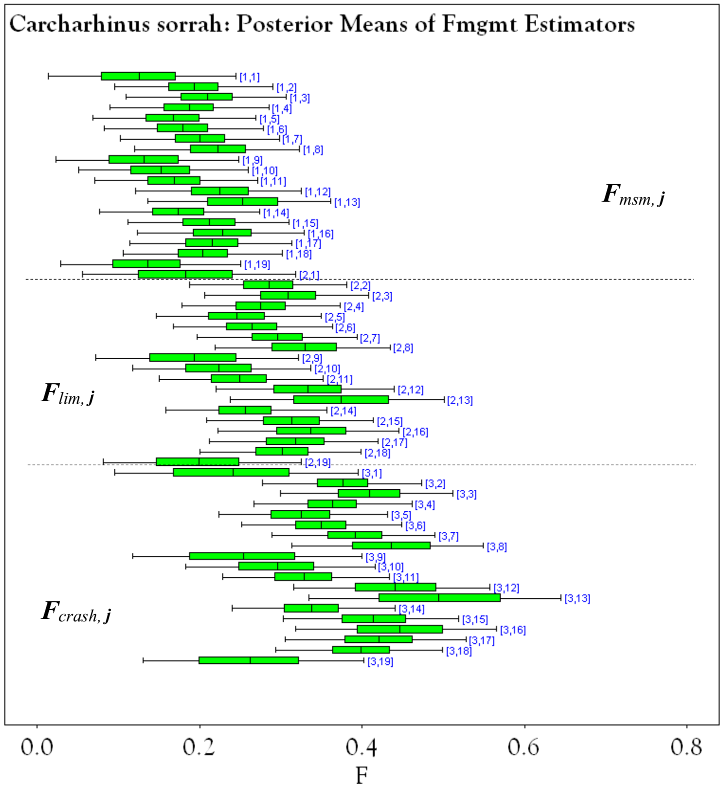
Figures A2–24a. *Carcharhinus sorrah* (Spottail Shark).

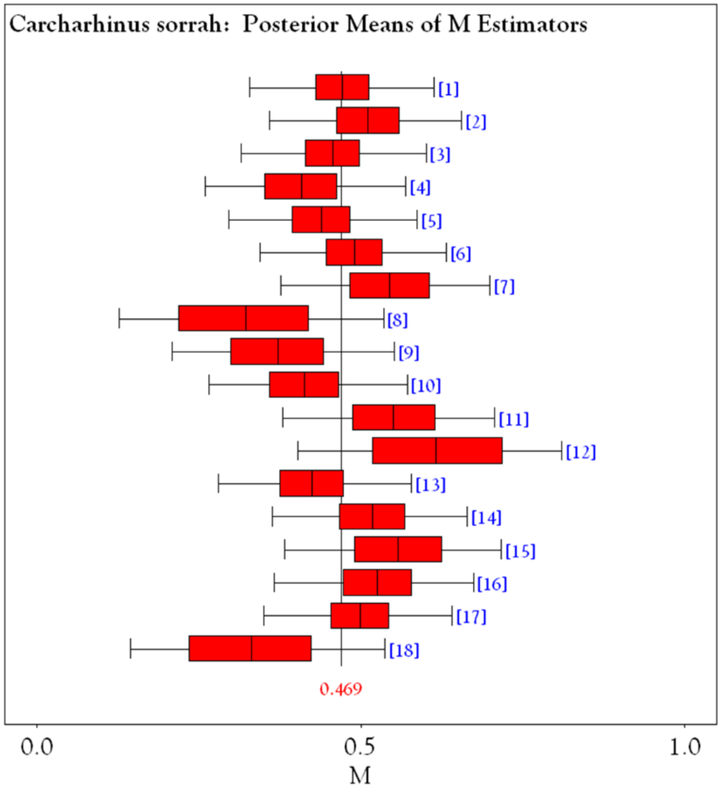


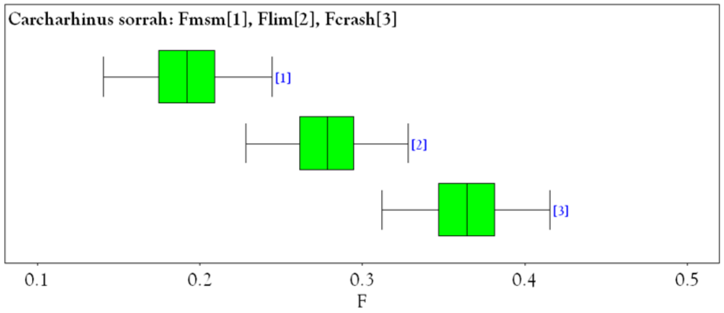


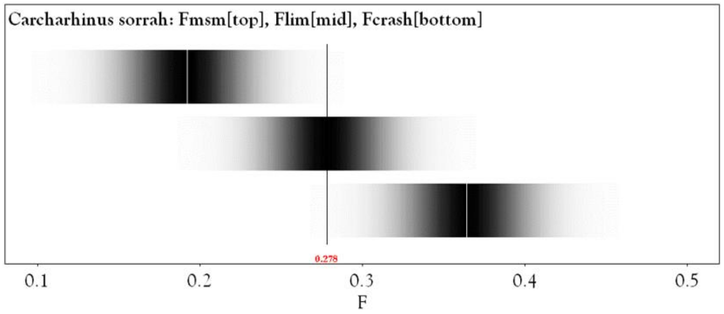
	n_{Total}	n_{Female}	μ	σ_{FW}
r	2	0	0.1184	0.0416
M_{lit}	1	1	0.4740	0.0000
K	1	0	0.3400	—
$L\infty$	4	0	150.96	18.65
L_{Max}	4	0	146.25	21.36
L_{mat}	1	1	120.00	0.00
$\bar{w}$	2	0	18.65	1.94
T_{Max}	2	0	7.46	0.77
T_{mat}	2	1	2.50	0.00
T [°C]	1	—	27.00	—
			$E[\hat{\mu}]$	$E[\hat{\sigma}^2]$
M_{est}	18	—	0.4695	0.1598
F_{msm}	19	—	0.1855	0.0706
F_{lim}	19	—	0.2782	0.1060
F_{crash}	19	—	0.3710	0.1413

Figures A2–24b. *Carcharhinus sorrah* (Spottail Shark).









Ancillary Appendix 3

Results Profile for Selected Species

A handful of species (8 in total) are given unique and more in-depth graphical profiles here in Ancillary Appendix 3. The species herein presented were not necessarily chosen or curated with respect to any particular rationale, other than there was not enough time to produce these graphical sets for all 30 species. Many of the data points are referenced or explicitly presented in other ways within the main body of the text, though, several figures, tables, and representations uniquely populate these profiles, making them as distinctly valuable, albeit with a few redundancies. The labeling scheme is similar to what was used in Ancillary Appendix 2, where A3 is the prefix for Ancillary Appendix 3's objects (Figures / Tables), to clearly separate its outputs from that which is included in main text; however, unlike Ancillary Appendix 2, the signifying number following the initial prefix is not related to the study's pervasive species nos. shorthand, and therefore just represents arbitrary encounter position within the standing list. The species included within this section are listed subsequently, along with their Ancillary Appendix 3 specific labels: *C. longimanus* (Table A3–1; Figures A3–1[a-d]); *G. cuvier* (Table A3–2; Figures A3–2[a-d]); *Isurus oxyrinchus* (Table A3–3; Figures A3–3[a-d]); *Sphyrna lewini* (Table A3–4; Figures A3–4[a-d]); *Prionace glauca* (Table A3–5; Figures A3–5[a-d]); *C. falciformis* (Table A3–6; Figures A3–6[a-d]); *C. obscurus* (Table A3–7; Figures A3–7[a-d]); and *Stegostoma fasciatum* (Table A3–8; Figures A3–8[a-d]).

Table A3–1

Carcharhinus longimanus (Poey, 1861)
Oceanic Whitetip Shark

		mean	*sd*	MC error	C.I. (lower)			median	C.I. (upper)		
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{(i,j)\in I\times J}}$	**0.1680**	1.77E-02	7.85E-05	0.1329	0.1389	0.1457	0.1680	0.1902	0.1969	0.2030
	$\boldsymbol{\sigma}^2_y$	3.22E-03	3.14E-03	4.99E-06	4.58E-04	5.88E-04	7.97E-04	2.36E-03	6.44E-03	8.59E-03	1.11E-02
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (F *or* F_i)	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2010}_{j\in\{1\ldots n\}}}$	0.1832	2.15E-02	8.23E-05	0.1410	0.1483	0.1565	0.1830	0.2100	0.2184	0.2263
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2011}_{j\in\{1\ldots n\}}}$	0.1583	1.90E-02	7.21E-05	0.1211	0.1276	0.1347	0.1581	0.1820	0.1895	0.1966
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2012}_{j\in\{1\ldots n\}}}$	0.1410	2.21E-02	7.48E-05	0.0915	0.1031	0.1143	0.1425	0.1664	0.1737	0.1806
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2013}_{j\in\{1\ldots n\}}}$	0.1642	2.37E-02	8.17E-05	0.1146	0.1251	0.1355	0.1649	0.1922	0.2010	0.2094
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2014}_{j\in\{1\ldots n\}}}$	0.1932	2.66E-02	9.18E-05	0.1403	0.1506	0.1612	0.1932	0.2253	0.2360	0.2466
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}^{AFI_\alpha}_{i\in\{1\ldots n\}}$	559025	135848	117.09	291431	353115	410935	559025	706820	764345	826295
Target (*km2*)	$\boldsymbol{\theta}^{AFI_\beta}_{i\in\{1\ldots n\}}$	549585	134579	114.84	286711	347215	403855	549585	695020	751955	813020
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2010}}$	17310	1996	7.81	13440	14120	14860	17270	19810	20630	21390
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2011}}$	17340	2039	7.82	13390	14090	14840	17290	19880	20730	21520
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2012}}$	16520	2560	8.76	10760	12130	13450	16670	19440	20330	21160
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2013}}$	16870	2401	8.39	11840	12930	14000	16920	19710	20620	21510
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2014}}$	17150	2334	8.35	12530	13440	14370	17130	19970	20940	21890
Post. mean avg. annl. Catch $\mathrm{YFT}^{\mathrm{IOTC}}_{\mathrm{Total}}$&$\mathrm{YFT}^{\mathrm{EEZ}}_{\mathrm{LL}}$('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{IOTC}_{Total}}_{C^{i\in\{1\ldots n\}}}$	369000	31540	27.25	307100	321400	334800	369000	403200	416600	430900
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{i\in\{1\ldots n\}}}$	17040	2053	8.29	13010	13800	14600	17040	19490	20300	21050

(**Cont.**) Table A3–1

Post. means of YFT^{IOTC} Fishing Mortality per yr.											
Inst. rate Fish Mort. (F or F_i)	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2010}}$	0.1280	2.17E-02	1.84E-05	0.0886	0.0920	0.0979	0.1281	0.1579	0.1636	0.1670
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2011}}$	0.1205	2.07E-02	1.78E-05	0.0832	0.0863	0.0917	0.1206	0.1491	0.1544	0.1574
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2012}}$	0.1371	2.29E-02	1.96E-05	0.0951	0.0990	0.1054	0.1372	0.1685	0.1748	0.1785
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2013}}$	0.1582	2.52E-02	2.18E-05	0.1107	0.1157	0.1235	0.1583	0.1926	0.2003	0.2051
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2014}}$	0.1855	2.78E-02	2.35E-05	0.1315	0.1381	0.1478	0.1856	0.2231	0.2324	0.2387
Posterior means of Catch Mechanism Variables											
	$\xi^{Encounterability}$	0.9990	1.01E-03	3.03E-06	0.9963	0.9970	0.9977	0.9993	0.9999	0.9999	1.0000
	$\xi^{Selectivity}$	0.9417	5.13E-02	4.47E-04	0.8095	0.8384	0.8704	0.9556	0.9929	0.9966	0.9983
	$\xi^{Post\text{-}CatchMortality}$	0.9742	2.45E-02	2.12E-04	0.9102	0.9248	0.9408	0.9815	0.9971	0.9986	0.9993

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); ***F$_i$*** [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i***); study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the Indian EEZ ofexperiencing LL fishing effort ≈ **35.76%**

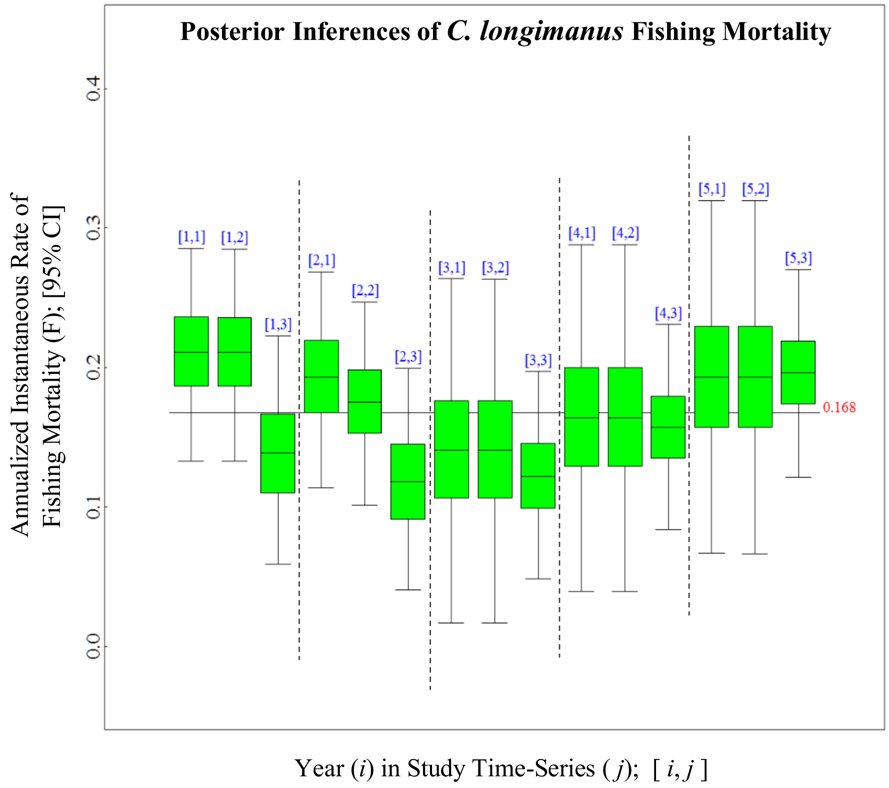


Figure A3–1a. Box Plots of Posterior Inferences of *Carcharhinus longimanus* Fishing Mortality by Year (*i*) and Individual Study Time-series (*j*) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: *i* = 1,...,5 is year 2010,…,2014; *j* = 1 is Abdussamad *et al.* (2012a & 2012b); *j* = 2 is Hornby *et al.*, (2015a & 2015b); *j* = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)].

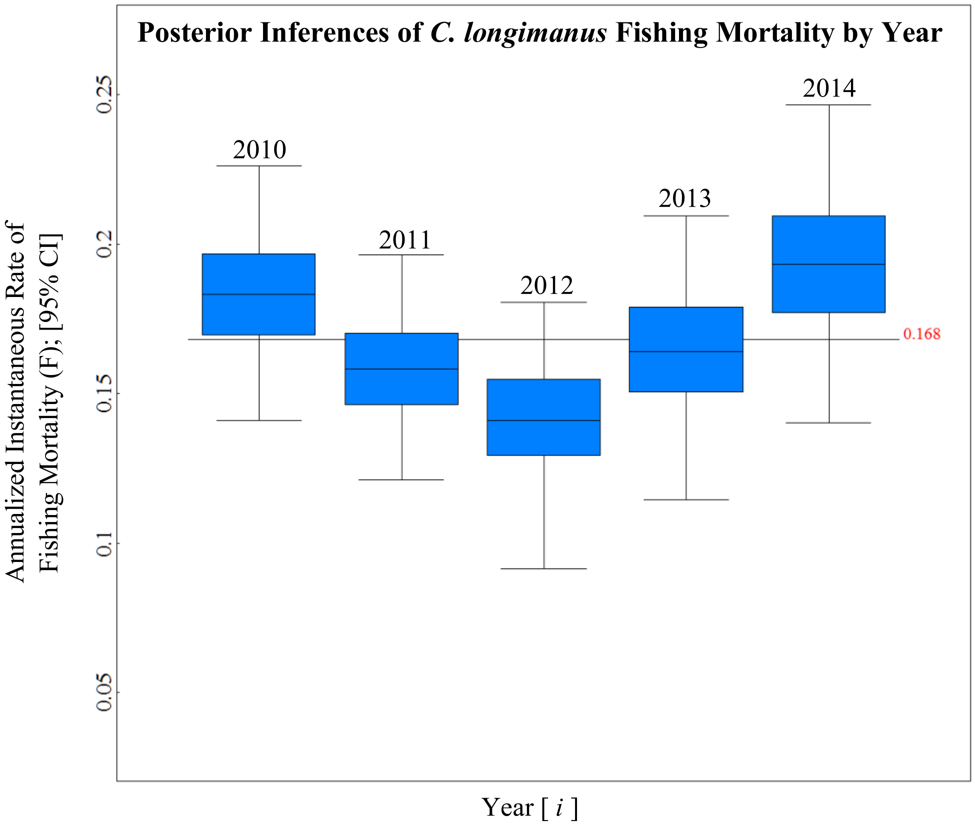


Figure A3–1b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *Carcharhinus longimanus* [2010-'14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

Oceanic Whitetip (*C. longimanus*) [Photo: Moldzio, S., 2011, (Egypt, Elphinstone Reef (Shaab Shagra); 180cm TL; as shown)] (http://www.fishbase.org)

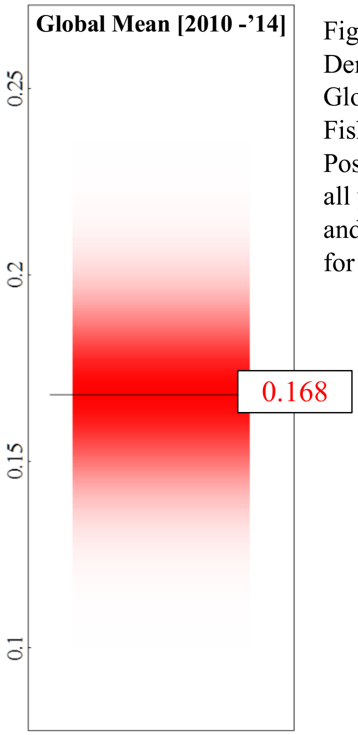


Figure A3–1c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-'14] and for all time-series for *C. longimanus.*

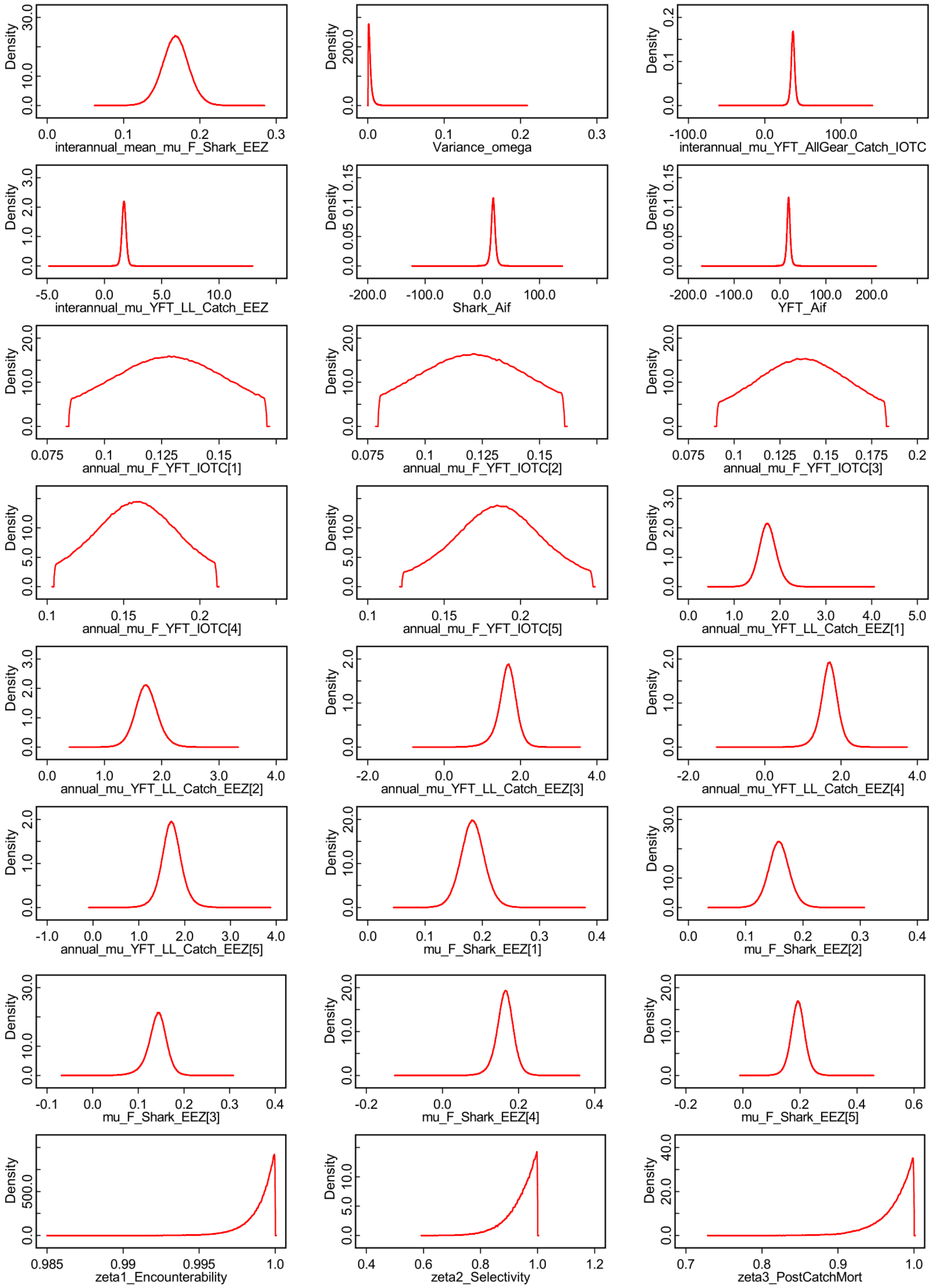


Figure A3–1d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Carcharhinus longimanus*.

Table Appx3–2

Galeocerdo cuvier (Péron & Lesueur, 1822)
Tiger Shark

		mean	*sd*	MC error		C.I. (lower)		median		C.I. (upper)	
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{(i,j)\in I\times J}}$	**0.1011**	1.87E-02	1.26E-04	0.0636	0.0706	0.0780	0.1011	0.1241	0.1316	0.1386
	$\boldsymbol{\sigma}^2_y$	1.70E-03	1.67E-03	3.28E-06	3.29E-04	4.01E-04	5.08E-04	1.24E-03	3.29E-03	4.45E-03	5.84E-03
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (F *or* F_i)	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2010}_{j\in\{1\ldots n\}}}$	0.1143	2.20E-02	1.41E-04	0.0709	0.0788	0.0874	0.1142	0.1415	0.1504	0.1588
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2011}_{j\in\{1\ldots n\}}}$	0.0787	1.58E-02	1.01E-04	0.0480	0.0535	0.0594	0.0784	0.0983	0.1048	0.1111
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2012}_{j\in\{1\ldots n\}}}$	0.0806	1.80E-02	1.03E-04	0.0438	0.0509	0.0584	0.0808	0.1024	0.1093	0.1160
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2013}_{j\in\{1\ldots n\}}}$	0.1287	2.69E-02	1.58E-04	0.0752	0.0850	0.0956	0.1286	0.1618	0.1725	0.1828
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2014}_{j\in\{1\ldots n\}}}$	0.1031	2.18E-02	1.29E-04	0.0605	0.0683	0.0766	0.1027	0.1298	0.1389	0.1477
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}^{AFI_\alpha}_{i\in\{1\ldots n\}}$	92070	21329	17.92	50209	59915	68942	92040	115227	124313	134048
Target (*km2*)	$\boldsymbol{\theta}^{AFI_\beta}_{i\in\{1\ldots n\}}$	549585	133930	114.61	286032	346920	404150	549880	695020	751660	812725
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2010}}$	17080	2582	17.10	12030	12920	13900	17050	20250	21320	22350
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2011}}$	17090	2609	16.45	11960	12890	13880	17060	20290	21370	22400
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2012}}$	16330	3020	16.98	9922	11260	12640	16440	19870	20990	22070
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2013}}$	16640	2882	17.57	10780	11910	13100	16670	20090	21230	22360
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2014}}$	16910	2901	17.21	11180	12260	13390	16890	20400	21620	22820
Post. mean avg. annl. Catch YFT$^{IOTC}_{Total}$&YFT$^{EEZ}_{LL}$('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{IOTC}_{Total}}_{C^{i\in\{1\ldots n\}}}$	369000	31630	27.49	307000	321400	334800	369000	403200	416600	430900
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{i\in\{1\ldots n\}}}$	16810	2605	17.22	11650	12630	13650	16810	19930	20970	21990

(Cont.) Table A3–2

Post. means of YFT^{IOTC} Fishing Mortality per yr.											
Inst. rate Fish Mort. (F or F_i)	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2010}}$	0.1280	2.17E-02	1.90E-05	0.0886	0.0920	0.0979	0.1281	0.1580	0.1637	0.1670
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2011}}$	0.1205	2.07E-02	1.78E-05	0.0832	0.0863	0.0917	0.1205	0.1491	0.1544	0.1574
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2012}}$	0.1371	2.28E-02	1.92E-05	0.0951	0.0990	0.1055	0.1372	0.1685	0.1748	0.1785
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2013}}$	0.1582	2.52E-02	2.13E-05	0.1107	0.1157	0.1235	0.1583	0.1927	0.2003	0.2050
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2014}}$	0.1855	2.78E-02	2.40E-05	0.1315	0.1381	0.1478	0.1856	0.2231	0.2324	0.2387
Posterior means of Catch Mechanism Variables											
	$\xi^{Encounterability}$	0.9990	1.00E-03	2.88E-06	0.9963	0.9970	0.9977	0.9993	0.9999	0.9999	1.0000
	$\xi^{Selectivity}$	0.5416	1.31E-01	1.18E-03	0.3110	0.3459	0.3854	0.5297	0.7173	0.7808	0.8349
	$\xi^{Post\text{-}Catch Mortality}$	0.8964	8.93E-02	7.57E-04	0.6687	0.7154	0.7683	0.9205	0.9872	0.9938	0.9969

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); ***F$_i$*** [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i***); study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the Indian EEZ ofexperiencing LL fishing effort ≈ **41.69%**

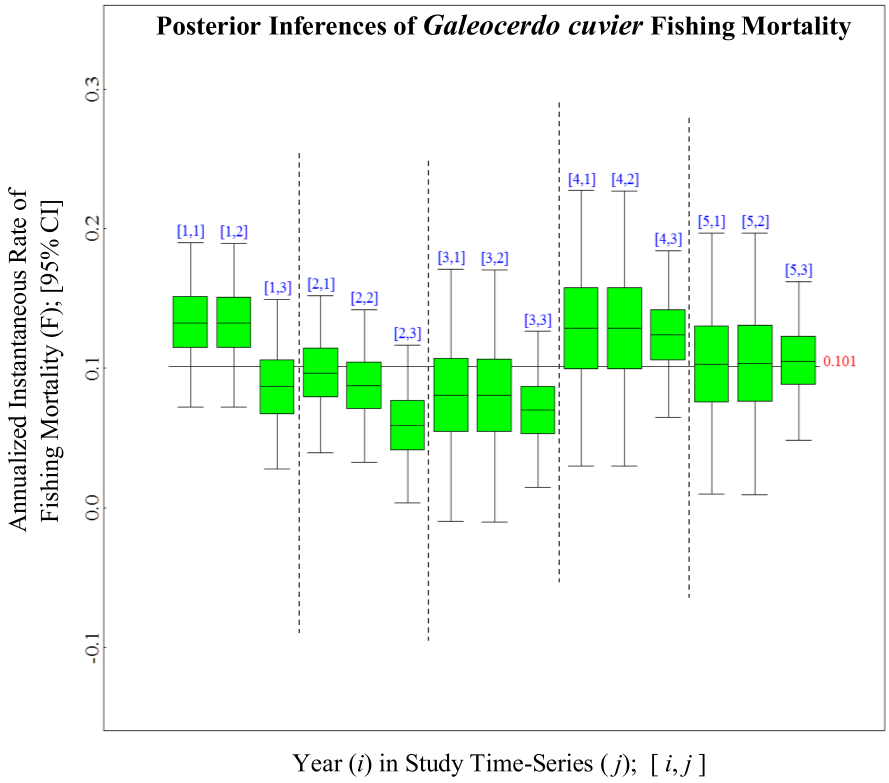


Figure A3–2a. Box Plots of Posterior Inferences of *Galeocerdo cuvier* Fishing Mortality by Year (*i*) and Individual Study Time-series (*j*) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: *i* = 1,...,5 is year 2010,…,2014; *j* = 1 is Abdussamad *et al.* (2012a & 2012b); *j* = 2 is Hornby *et al.*, (2015a & 2015b); *j* = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)].

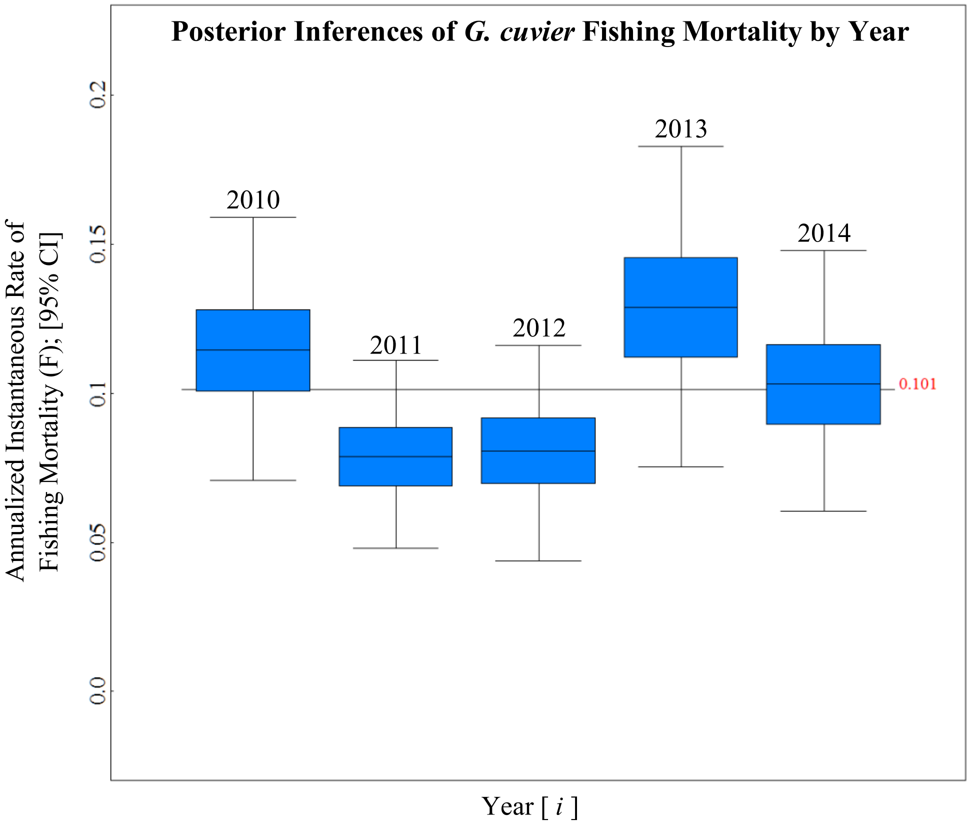


Figure A3–2b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *Galeocerdo cuvier* [2010-'14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

Tiger Shark (*Galeocerdo cuvier*)
[Photo: Kok, A., 2010, (Grand Bahamas)]
(https://commons.wikimedia.org
/w/index.php?curid=8969258)

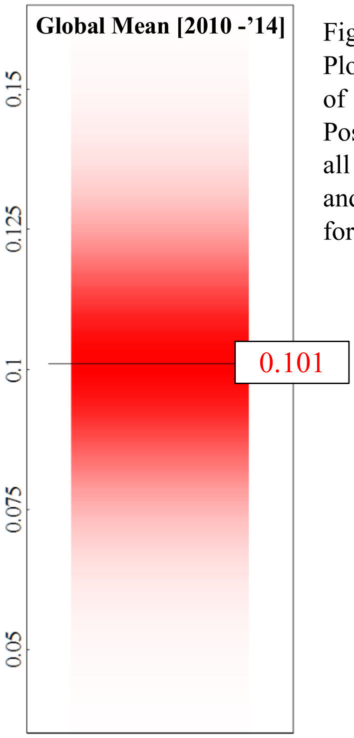


Figure A3–2c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-'14] and for all time-series for *G. cuvier*.

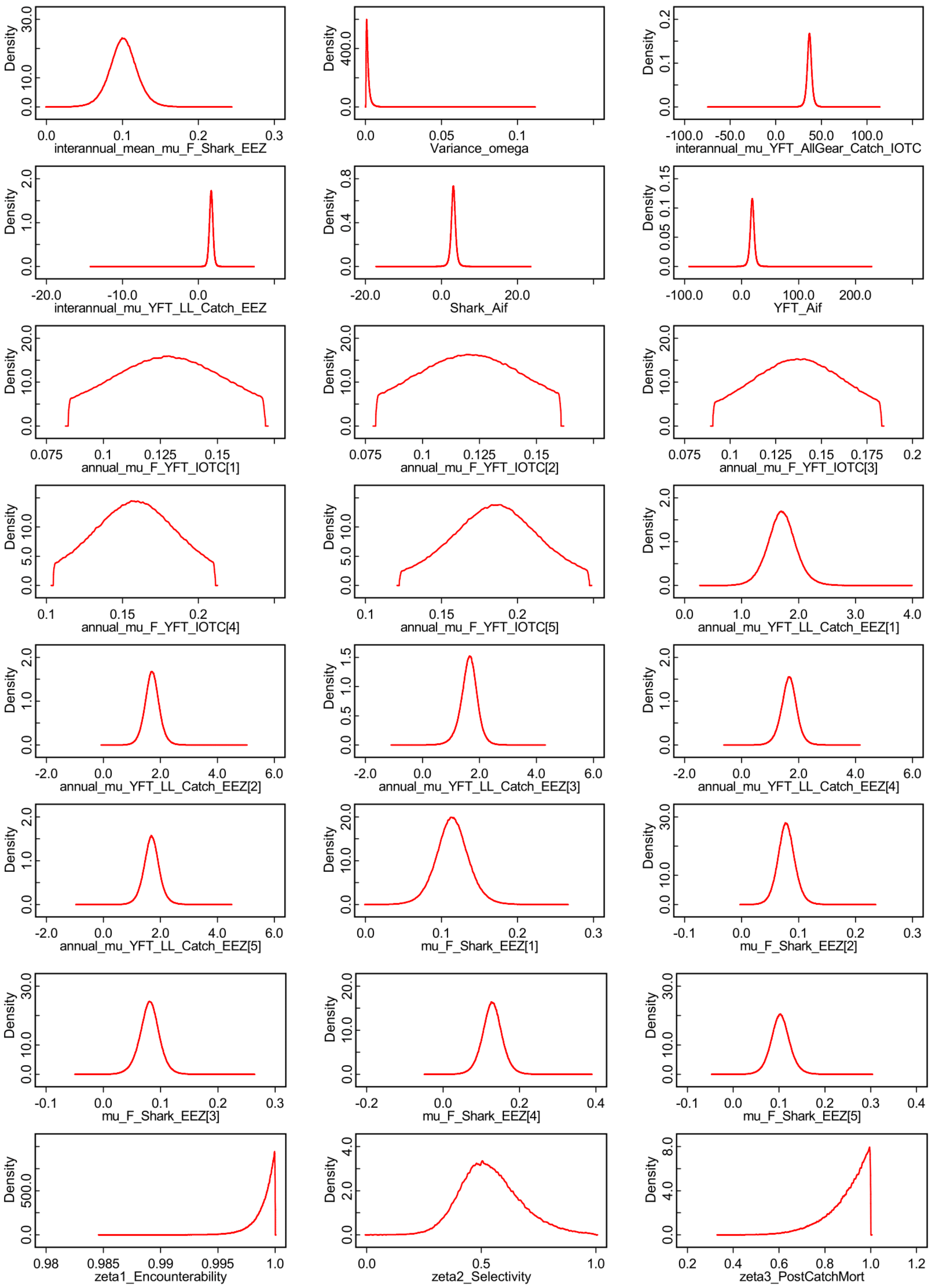


Figure A3–2d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Galeocerdo cuvier*.

Table A3–3

Isurus oxyrinchus (Rafinesque, 1810)
Shortfin Mako

		mean	*sd*	MC error		C.I. (lower)		median		C.I. (upper)	
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}_{F^{(i,j)\in I\times J}}^{Shark_{LL}^{EEZ}}$	**0.1768**	1.78E-02	9.21E-05	0.1416	0.1478	0.1546	0.1768	0.1989	0.2057	0.212
	$\boldsymbol{\sigma}_y^2$	3.46E-03	3.39E-03	7.12E-06	4.69E-04	6.05E-04	8.29E-04	2.55E-03	6.98E-03	9.27E-03	1.19E-02
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (F *or* F_i)	$\boldsymbol{\mu}_{F_{j\in\{1\dots n\}}^{2010}}^{Shark_{LL}^{EEZ}}$	0.1921	2.17E-02	9.56E-05	0.1495	0.1571	0.1653	0.1919	0.219	0.2278	0.2359
	$\boldsymbol{\mu}_{F_{j\in\{1\dots n\}}^{2011}}^{Shark_{LL}^{EEZ}}$	0.1668	1.93E-02	8.37E-05	0.1292	0.1359	0.1431	0.1666	0.1908	0.1986	0.206
	$\boldsymbol{\mu}_{F_{j\in\{1\dots n\}}^{2012}}^{Shark_{LL}^{EEZ}}$	0.1484	2.28E-02	9.07E-05	0.0969	0.1091	0.1209	0.15	0.1742	0.1818	0.1891
	$\boldsymbol{\mu}_{F_{j\in\{1\dots n\}}^{2013}}^{Shark_{LL}^{EEZ}}$	0.1729	2.43E-02	9.74E-05	0.1216	0.1327	0.1437	0.1737	0.2014	0.2105	0.2194
	$\boldsymbol{\mu}_{F_{j\in\{1\dots n\}}^{2014}}^{Shark_{LL}^{EEZ}}$	0.2037	2.74E-02	1.09E-04	0.1489	0.1599	0.171	0.2037	0.2364	0.2477	0.2588
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}_{i\in\{1\dots n\}}^{AFI_a}$	549290	1.34E+05	1.46E+02	286858	347510	404150	549585	695020	750775	812135
Target (*km2*)	$\boldsymbol{\theta}_{i\in\{1\dots n\}}^{AFI_\beta}$	549585	1.34E+05	1.46E+02	287419	348100	404740	549585	694430	750775	811545
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}_{C^{2010}}^{Tuna_{LL}^{EEZ}}$	17310	1.95E+03	8.51E+00	13500	14170	14920	17290	19730	20530	21270
	$\boldsymbol{\mu}_{C^{2011}}^{Tuna_{LL}^{EEZ}}$	17340	1.99E+03	8.44E+00	13440	14140	14900	17310	19820	20630	21400
	$\boldsymbol{\mu}_{C^{2012}}^{Tuna_{LL}^{EEZ}}$	16510	2.53E+03	9.91E+00	10780	12150	13460	16690	19370	20220	21040
	$\boldsymbol{\mu}_{C^{2013}}^{Tuna_{LL}^{EEZ}}$	16870	2.36E+03	9.30E+00	11880	12960	14030	16940	19640	20530	21410
	$\boldsymbol{\mu}_{C^{2014}}^{Tuna_{LL}^{EEZ}}$	17150	2.30E+03	9.13E+00	12550	13470	14410	17150	19900	20850	21790
Post. mean avg. annl. Catch YFT^{IOTC}_{Total}&YFT^{EEZ}_{LL}('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}_{C^{i\in\{1\dots n\}}}^{Tuna_{Total}^{IOTC}}$	369000	3.14E+04	3.38E+01	307200	321500	334800	369100	403300	416600	431000
	$\boldsymbol{\mu}_{C^{i\in\{1\dots n\}}}^{Tuna_{LL}^{EEZ}}$	17040	2008	9.199	13050	13840	14650	17060	19410	20180	20930

(**Cont.**) Table A3–3

Post. means of YFT^{IOTC} Fishing Mortality per yr.											
Inst. rate Fish Mort. (F or F_i)	$\mu_{F^{2010}}^{Tuna_{Total}^{IOTC}}$	0.128	2.17E-02	2.31E-05	0.0886	0.0920	0.0978	0.1281	0.1579	0.1637	0.167
	$\mu_{F^{2011}}^{Tuna_{Total}^{IOTC}}$	0.1204	2.07E-02	2.21E-05	0.0831	0.0862	0.0916	0.1205	0.1491	0.1544	0.1574
	$\mu_{F^{2012}}^{Tuna_{Total}^{IOTC}}$	0.1371	2.29E-02	2.51E-05	0.0951	0.099	0.1054	0.1372	0.1686	0.1749	0.1785
	$\mu_{F^{2013}}^{Tuna_{Total}^{IOTC}}$	0.1583	2.53E-02	2.78E-05	0.1107	0.1157	0.1235	0.1584	0.1927	0.2004	0.2051
	$\mu_{F^{2014}}^{Tuna_{Total}^{IOTC}}$	0.1855	2.78E-02	3.06E-05	0.1314	0.138	0.1477	0.1856	0.2231	0.2324	0.2387
Posterior means of Catch Mechanism Variables											
	$\xi^{Encounterability}$	0.999	9.99E-04	4.20E-06	0.9963	0.997	0.9977	0.9993	0.9999	0.9999	1
	$\xi^{Selectivity}$	0.9704	2.80E-02	3.53E-04	0.8968	0.9137	0.9323	0.9787	0.9966	0.9984	0.9992
	$\xi^{Post\text{-}CatchMortality}$	0.9941	5.84E-03	5.15E-05	0.9783	0.9823	0.9864	0.9958	0.9994	0.9997	0.9999

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); ***F**$_i$* [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i***); study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the Indian EEZ ofexperiencing LL fishing effort $\approx$ **35.71%**

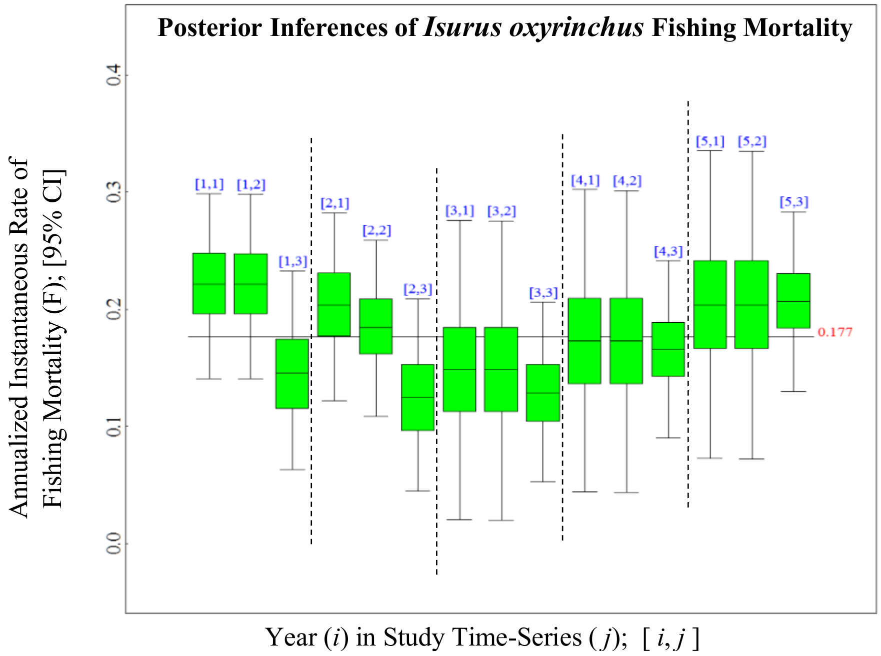


Figure A3–3a. Box Plots of Posterior Inferences of *Isurus oxyrinchus* Fishing Mortality by Year (i) and Individual Study Time-series (j) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: i = 1,...,5 is year 2010,…,2014; j = 1 is Abdussamad *et al.* (2012a & 2012b); j = 2 is Hornby *et al.*, (2015a & 2015b); j = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)]

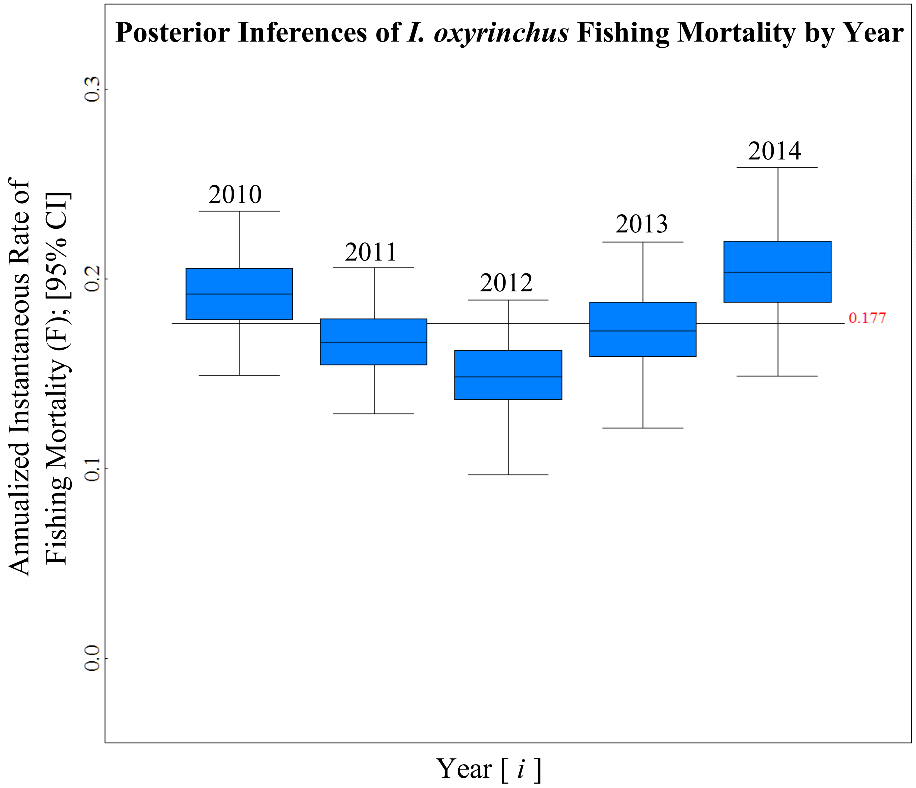


Figure A3–3b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *I. oxyrinchus* [2010-’14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

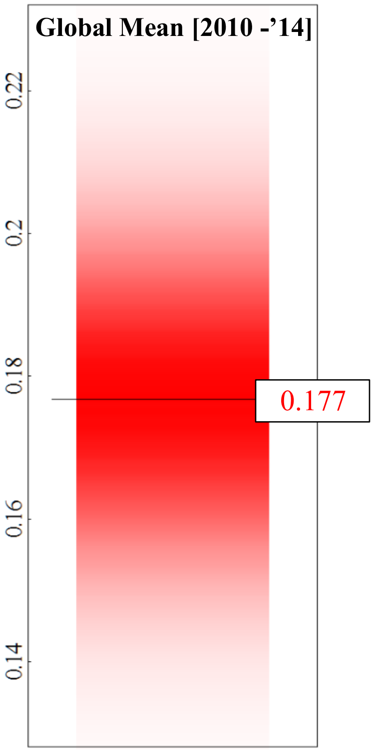


Figure A3–3c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-’14] and for all time-series for *I. oxyrinchus*.

Shortfin Mako (*I. oxyrinchus*) (De Maddalena, A. 2014) (http://www.alessandrodemaddalena.com)

Species Notes: A generally large and impressive shark of the Lamnidae family, the Shortfin Mako is cosmopolitan in temperate and tropical seas worldwide, both coastal and oceanic. **Traits:** Pointed snout; dark blue from above and white below, with large black eyes and lunate caudal fin with thick lower lobe. **Habitat:** Oceanic, but can patrol inshore into littoral zones in places with narrow continental shelfs especially. Coastal and oceanic associated and epipelagic. Lower depth maxima likely 750m but most frequently resides between 100-150m. *I. oxyrinchus* is oceanodromous and a highly migratory oceanic commuter through its extensive range; though, the nature of these movements are less well understood (Compagno, 2002). **Locomotion:** An extremely agile and athletic species when triggered by predation opportunities; renowned for highly acrobatic, areal breaches when in pursuit of prey and is likely the fastest shark on earth. **Diet:** Mostly piscivorous, eating smaller-/medium-sized schooling fish (mackerel, sardines, tunnies, etc.) as well as large predatory fish (billfishes and other sharks sometimes). **Fisheries:** Utilized fresh, dried or salted, smoked and frozen and valued for its fine quality meat as well as its fins and skin. Oil is extracted for vitamins and fins for shark-fin soup. Jaws and teeth are also sold as ornaments and trophies. Increasingly impacted through by-catch or targeted fishing where applicable. **Status:** ICUN Vulnerable (VU); CMS Appendix II protected species.

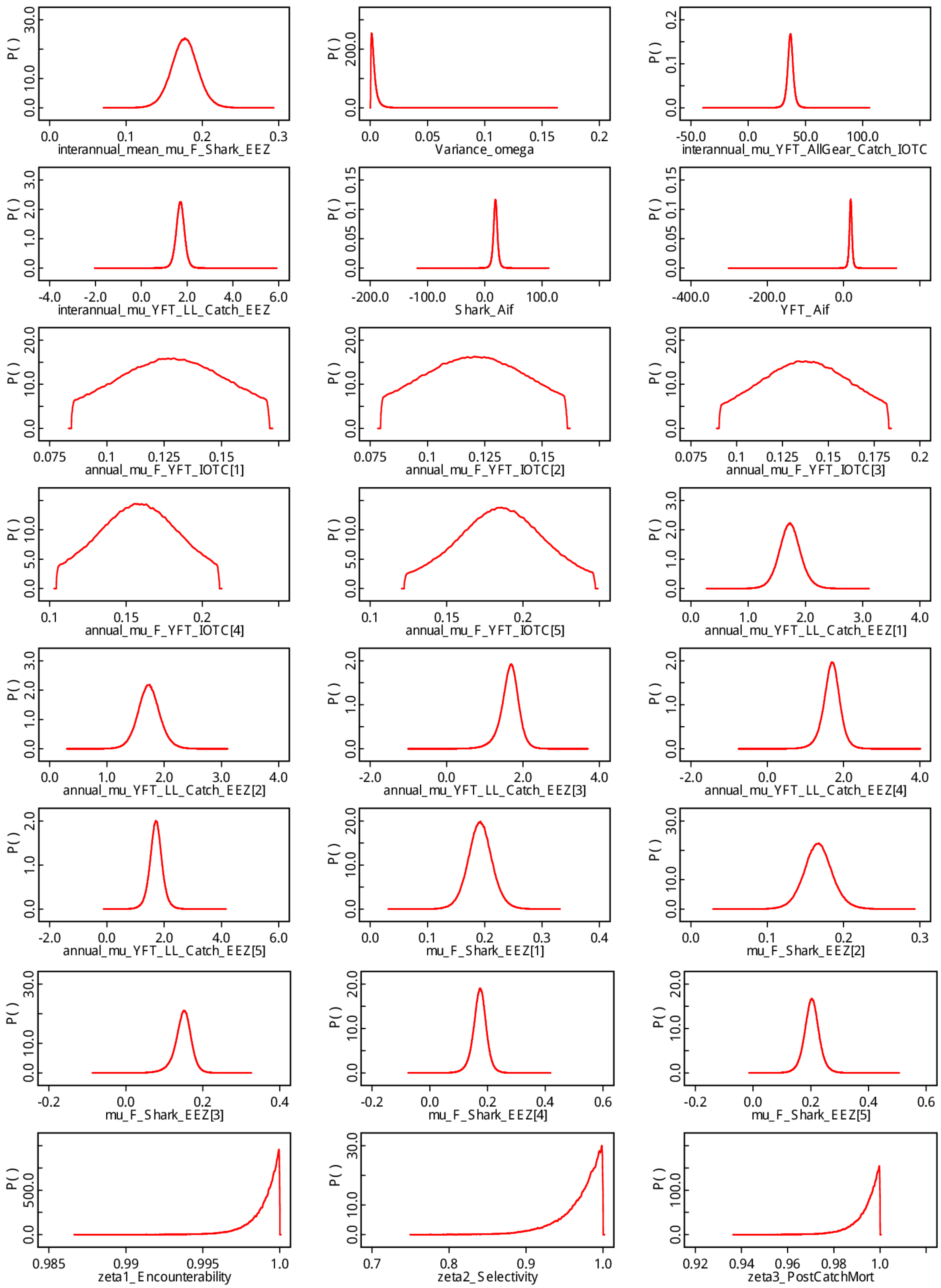


Figure A3–3d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Isurus oxyrinchus*.

Table A3–4

Sphyrna lewini (Griffith & Smith, 1834)
Scalloped Hammerhead

		mean	*sd*	MC error		C.I. (lower)		median		C.I. (upper)	
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}^{Shark_{LL}^{EEZ}}_{F^{(i,j)\in I\times J}}$	**0.0450**	1.40E-02	1.19E-04	0.0164	0.0216	0.0274	0.0452	0.0622	0.0677	0.0728
	$\boldsymbol{\sigma}^2_y$	9.86E-04	9.21E-04	2.38E-06	2.33E-04	2.75E-04	3.35E-04	7.33E-04	1.86E-03	2.50E-03	3.27E-03
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (F *or* F_i)	$\boldsymbol{\mu}^{Shark_{LL}^{EEZ}}_{F^{2010}_{j\in\{1 \dots n\}}}$	0.0511	1.62E-02	1.34E-04	0.0184	0.0243	0.0308	0.0512	0.0711	0.0775	0.0835
	$\boldsymbol{\mu}^{Shark_{LL}^{EEZ}}_{F^{2011}_{j\in\{1 \dots n\}}}$	0.0360	1.16E-02	9.59E-05	0.0129	0.0170	0.0215	0.0359	0.0504	0.0551	0.0595
	$\boldsymbol{\mu}^{Shark_{LL}^{EEZ}}_{F^{2012}_{j\in\{1 \dots n\}}}$	0.0363	1.24E-02	9.67E-05	0.0118	0.0160	0.0208	0.0363	0.0517	0.0566	0.0612
	$\boldsymbol{\mu}^{Shark_{LL}^{EEZ}}_{F^{2013}_{j\in\{1 \dots n\}}}$	0.0572	1.89E-02	1.50E-04	0.0196	0.0262	0.0335	0.0571	0.0806	0.0882	0.0954
	$\boldsymbol{\mu}^{Shark_{LL}^{EEZ}}_{F^{2014}_{j\in\{1 \dots n\}}}$	0.0445	1.48E-02	1.18E-04	0.0154	0.0204	0.0261	0.0444	0.0629	0.0689	0.0748
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}^{AFI_a}_{i\in\{1 \dots n\}}$	110596	26140	28.10	59207	71213	82246	110596	138975	149978	161837
Target (*km2*)	$\boldsymbol{\theta}^{AFI_\beta}_{i\in\{1 \dots n\}}$	549585	134284	148.21	286121	347510	404150	549880	694725	751660	813315
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna_{LL}^{EEZ}}_{C^{2010}}$	17190	2682	16.17	11900	12880	13930	17160	20460	21580	22670
	$\boldsymbol{\mu}^{Tuna_{LL}^{EEZ}}_{C^{2011}}$	17210	2702	15.72	11860	12870	13930	17180	20500	21620	22710
	$\boldsymbol{\mu}^{Tuna_{LL}^{EEZ}}_{C^{2012}}$	16470	3187	16.96	9603	11140	12650	16610	20130	21320	22480
	$\boldsymbol{\mu}^{Tuna_{LL}^{EEZ}}_{C^{2013}}$	16790	3056	16.93	10500	11800	13110	16830	20380	21620	22840
	$\boldsymbol{\mu}^{Tuna_{LL}^{EEZ}}_{C^{2014}}$	17030	3073	16.74	10880	12130	13390	17020	20660	21960	23260
Post. mean avg. annl. Catch $\mathrm{YFT}^{\mathrm{IOTC}}_{\mathrm{Total}}$&$\mathrm{YFT}^{\mathrm{EEZ}}_{\mathrm{LL}}$('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna_{Total}^{IOTC}}_{C^{i\in\{1 \dots n\}}}$	369100	31490	34.46	307200	321500	334900	369100	403200	416500	431000
	$\boldsymbol{\mu}^{Tuna_{LL}^{EEZ}}_{C^{i\in\{1 \dots n\}}}$	16940	2704	16.74	11560	12600	13710	16950	20130	21220	22300

(**Cont.**) Table A3–4

Post. means of $\mathrm{YFT}^{\mathrm{IOTC}}$ Fishing Mortality per yr.											
Inst. rate Fish Mort. $(F \ or \ F_i)$	$\boldsymbol{\mu}_{F^{2010}}^{Tuna_{Total}^{IOTC}}$	0.1280	2.17E-02	2.41E-05	0.0886	0.0920	0.0979	0.1281	0.1580	0.1637	0.1670
	$\boldsymbol{\mu}_{F^{2011}}^{Tuna_{Total}^{IOTC}}$	0.1204	2.07E-02	2.19E-05	0.0832	0.0863	0.0917	0.1205	0.1491	0.1543	0.1573
	$\boldsymbol{\mu}_{F^{2012}}^{Tuna_{Total}^{IOTC}}$	0.1371	2.28E-02	2.46E-05	0.0951	0.0990	0.1055	0.1372	0.1684	0.1748	0.1785
	$\boldsymbol{\mu}_{F^{2013}}^{Tuna_{Total}^{IOTC}}$	0.1582	2.52E-02	2.66E-05	0.1107	0.1157	0.1236	0.1584	0.1927	0.2003	0.2051
	$\boldsymbol{\mu}_{F^{2014}}^{Tuna_{Total}^{IOTC}}$	0.1855	2.78E-02	2.99E-05	0.1315	0.1381	0.1478	0.1856	0.2230	0.2324	0.2387
Posterior means of Catch Mechanism Variables											
	$\boldsymbol{\xi}^{Encounterability}$	0.9990	9.92E-04	3.71E-06	0.9963	0.9970	0.9977	0.9993	0.9999	0.9999	1.0000
	$\boldsymbol{\xi}^{Selectivity}$	0.2399	8.76E-02	8.46E-04	0.0825	0.1094	0.1374	0.2331	0.3503	0.3929	0.4362
	$\boldsymbol{\xi}^{Post\text{-}CatchMortality}$	0.8719	1.10E-01	1.18E-03	0.5915	0.6486	0.7153	0.9013	0.9840	0.9922	0.9961

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); $\boldsymbol{F_i}$ [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i*** **);** study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the Indian EEZ ofexperiencing LL fishing effort $\approx$ **43.36%**

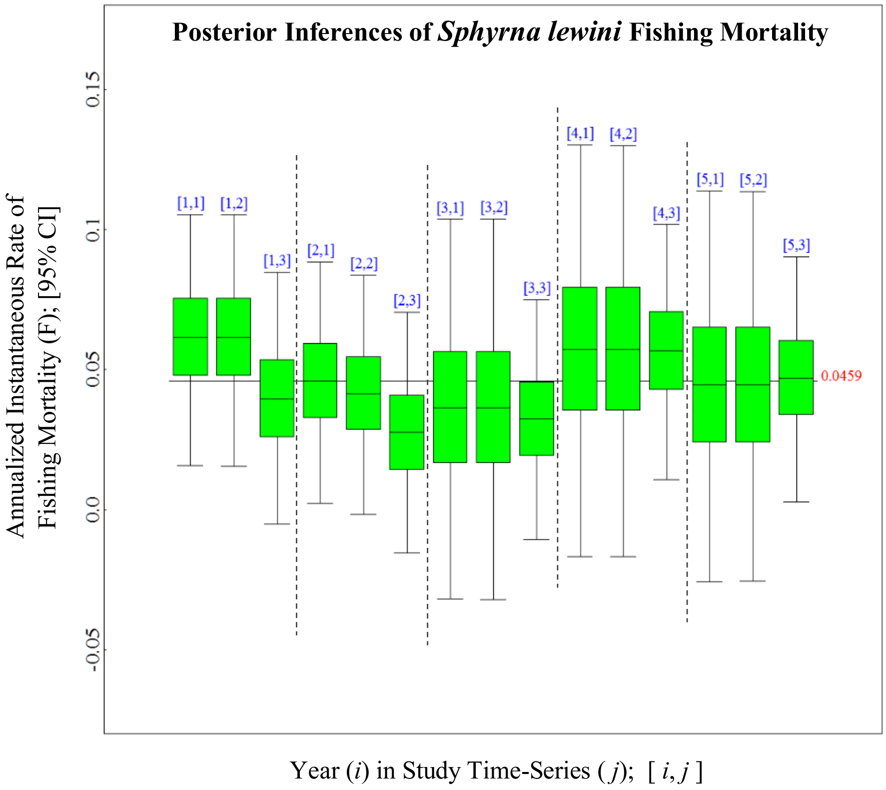


Figure A3–4a. Box Plots of Posterior Inferences of *Sphyrna lewini* Fishing Mortality by Year (*i*) and Individual Study Time-series (*j*) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: *i* = 1,...,5 is year 2010,…,2014; *j* = 1 is Abdussamad *et al.* (2012a & 2012b); *j* = 2 is Hornby *et al.*, (2015a & 2015b); *j* = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)].

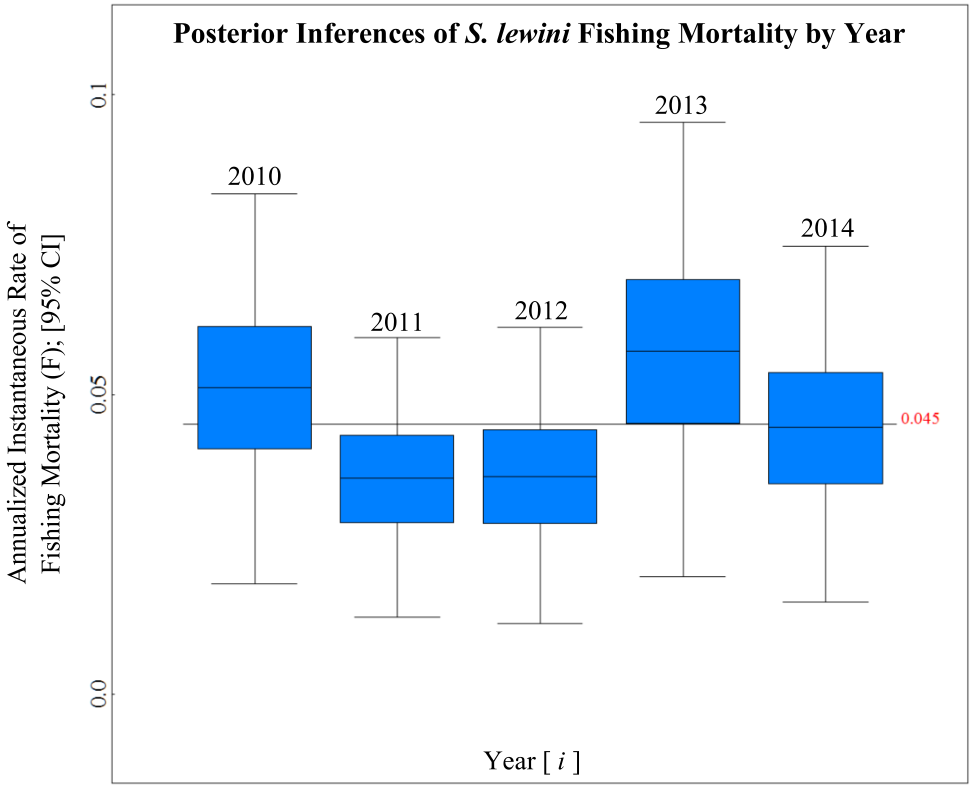


Figure A3–4b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *Sphyrna lewini* [2010-'14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

Scalloped Hammerhead (*Sphyrna lewini*) [Photo: Peters, B., 1999; (Cocos Island, Coasta Rica)] (https://commons.wikimedia.org/w/index.php?curid=8919188)

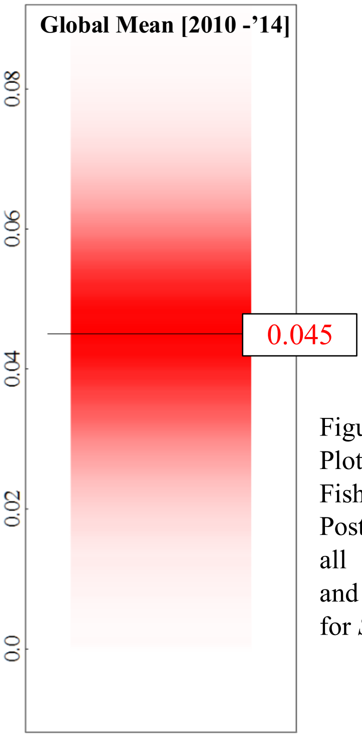


Figure A3–4c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-'14] and for all time-series for *Sphyrna lewini.*

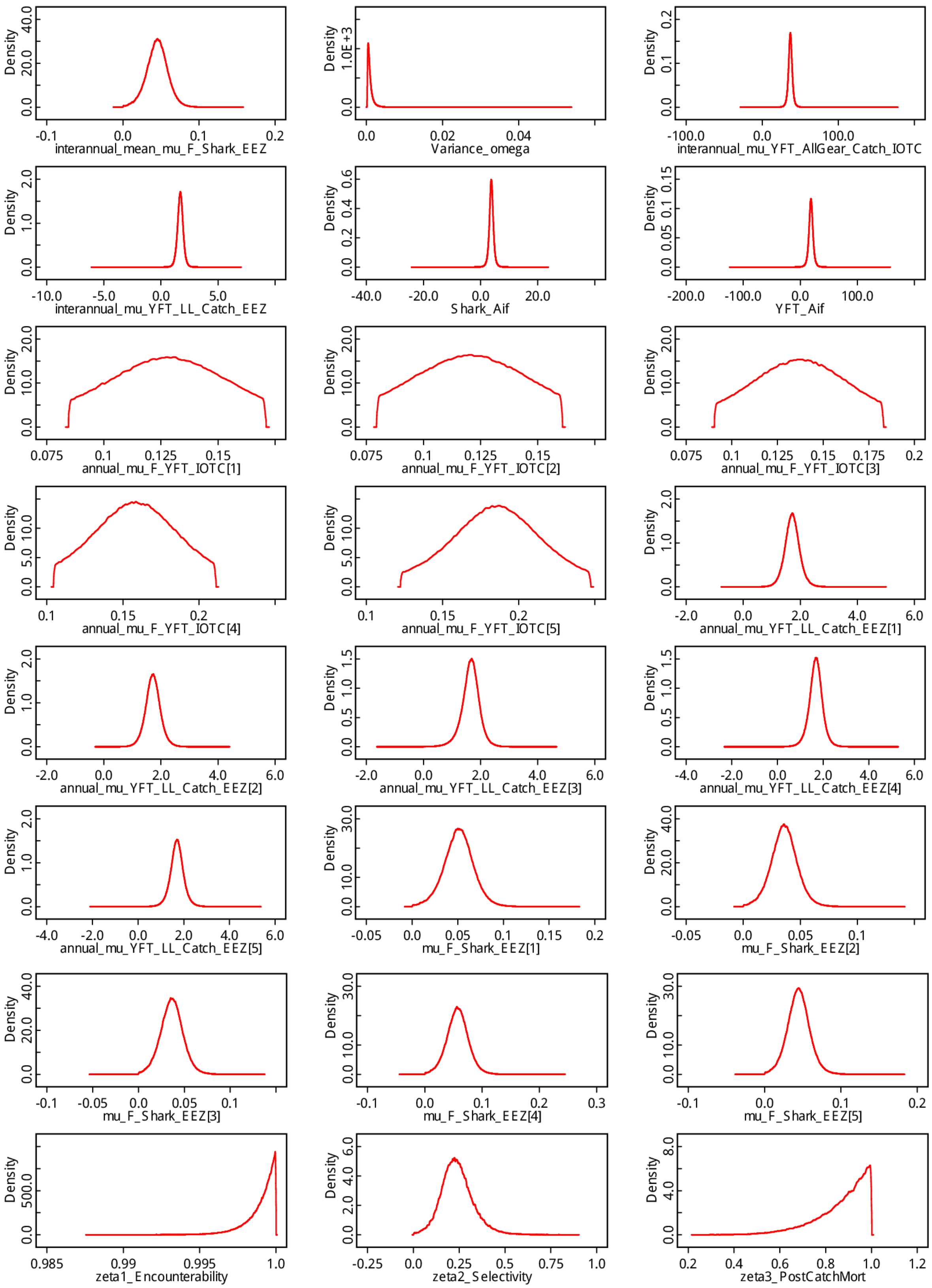


Figure A3–4d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Sphyrna lewini*.

Table A3–5

Prionace glauca (Linnaeus, 1758)
Blue Shark

		mean	*sd*	MC error		C.I. (lower)		median		C.I. (upper)	
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{(i,j)\in I\times J}}$	**0.1852**	1.83E-02	9.44E-05	0.1489	0.1552	0.1622	0.1852	0.2081	0.2150	0.2214
	$\boldsymbol{\sigma}^2_y$	3.83E-03	3.80E-03	7.60E-06	4.89E-04	6.38E-04	8.83E-04	2.81E-03	7.75E-03	1.03E-02	1.33E-02
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (F *or* F_i)	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2010}_{j\in\{1\ldots n\}}}$	0.2008	2.24E-02	9.66E-05	0.1569	0.1647	0.1731	0.2006	0.2287	0.2376	0.2459
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2011}_{j\in\{1\ldots n\}}}$	0.1823	2.07E-02	8.89E-05	0.1419	0.1491	0.1569	0.1821	0.2081	0.2165	0.2244
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2012}_{j\in\{1\ldots n\}}}$	0.1569	2.39E-02	9.39E-05	0.1026	0.1157	0.1282	0.1587	0.1839	0.1918	0.1992
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2013}_{j\in\{1\ldots n\}}}$	0.1792	2.50E-02	9.98E-05	0.1265	0.1380	0.1492	0.1800	0.2084	0.2178	0.2270
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2014}_{j\in\{1\ldots n\}}}$	0.2066	2.76E-02	1.10E-04	0.1514	0.1624	0.1736	0.2066	0.2395	0.2508	0.2620
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}^{AFI_\alpha}_{i\in\{1\ldots n\}}$	626285	159153	171.69	313880	387040	454300	626285	798565	866120	939575
Target (*km2*)	$\boldsymbol{\theta}^{AFI_\beta}_{i\in\{1\ldots n\}}$	549880	134314	146.79	285649	346625	403855	549880	695315	752545	813610
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2010}}$	17310	1924	8.21	13530	14200	14930	17290	19700	20470	21190
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2011}}$	17340	1962	8.34	13510	14180	14920	17320	19780	20580	21330
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2012}}$	16500	2507	9.79	10790	12170	13480	16690	19340	20160	20950
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2013}}$	16870	2347	9.31	11920	12990	14050	16940	19610	20500	21350
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2014}}$	17140	2286	9.02	12570	13480	14410	17140	19870	20800	21730
Post. mean avg. annl. Catch $\text{YFT}^{\text{IOTC}}_{\text{Total}}$&$\text{YFT}^{\text{EEZ}}_{\text{LL}}$('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{IOTC}_{Total}}_{C^{i\in\{1\ldots n\}}}$	369000	31410	33.54	307300	321500	334900	369000	403100	416400	430700
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{i\in\{1\ldots n\}}}$	17030	1980	9.06	13090	13870	14660	17060	19380	20130	20840

(**Cont.**) Table A3–5

Post. means of YFT^{IOTC} Fishing Mortality per yr.											
Inst. rate Fish Mort. (F or F_i)	$\mu_{F^{2010}}^{Tuna_{Total}^{IOTC}}$	0.1280	2.17E-02	2.32E-05	0.0886	0.0920	0.0979	0.1281	0.1580	0.1637	0.1670
	$\mu_{F^{2011}}^{Tuna_{Total}^{IOTC}}$	0.1205	2.07E-02	2.23E-05	0.0832	0.0863	0.0917	0.1206	0.1491	0.1544	0.1573
	$\mu_{F^{2012}}^{Tuna_{Total}^{IOTC}}$	0.1371	2.28E-02	2.47E-05	0.0951	0.0990	0.1054	0.1372	0.1685	0.1748	0.1785
	$\mu_{F^{2013}}^{Tuna_{Total}^{IOTC}}$	0.1583	2.52E-02	2.69E-05	0.1108	0.1158	0.1236	0.1583	0.1927	0.2004	0.2051
	$\mu_{F^{2014}}^{Tuna_{Total}^{IOTC}}$	0.1855	2.78E-02	3.00E-05	0.1315	0.1380	0.1477	0.1856	0.2230	0.2324	0.2387
Posterior means of Catch Mechanism Variables											
	$\xi^{Encounterability}$	0.9990	9.97E-04	4.27E-06	0.9963	0.9970	0.9977	0.9993	0.9999	0.9999	1.0000
	$\xi^{Selectivity}$	0.9960	4.04E-03	3.21E-05	0.9850	0.9878	0.9907	0.9972	0.9996	0.9998	0.9999
	$\xi^{Post\text{-}CatchMortality}$	0.9844	1.50E-02	1.95E-04	0.9436	0.9543	0.9645	0.9889	0.9983	0.9992	0.9996

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); ***F$_i$*** [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i***); study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the Indian EEZ ofexperiencing LL fishing effort ≈ **37.12%**

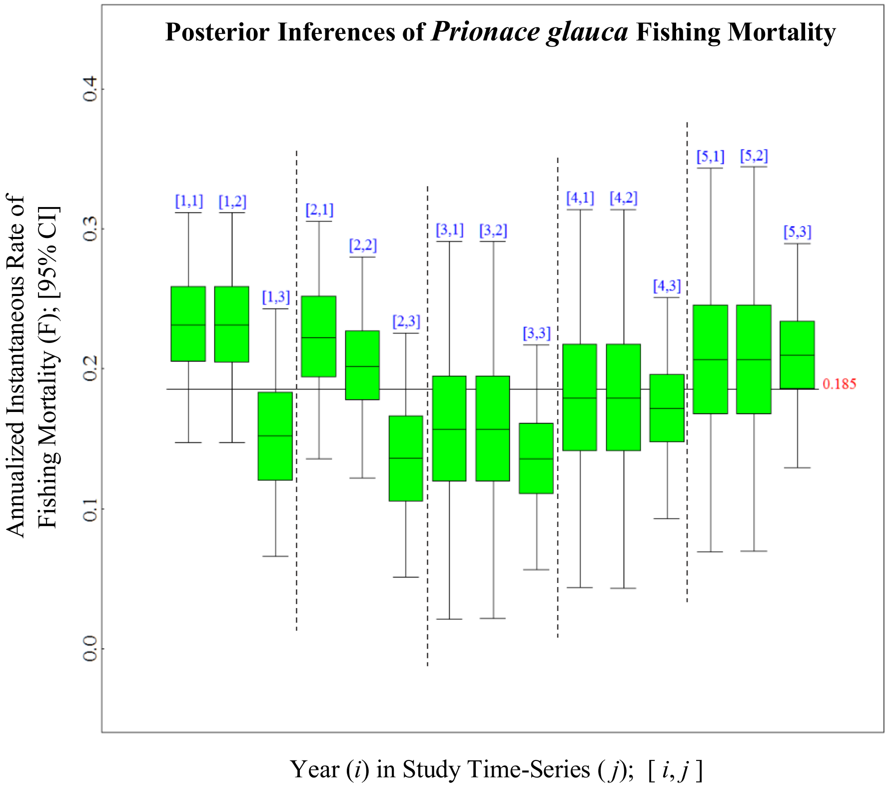


Figure A3–5a. Box Plots of Posterior Inferences of *Prionace glauca* Fishing Mortality by Year (*i*) and Individual Study Time-series (*j*) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: *i* = 1,...,5 is year 2010,…,2014; *j* = 1 is Abdussamad *et al.* (2012a & 2012b); *j* = 2 is Hornby *et al.*, (2015a & 2015b); *j* = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)].

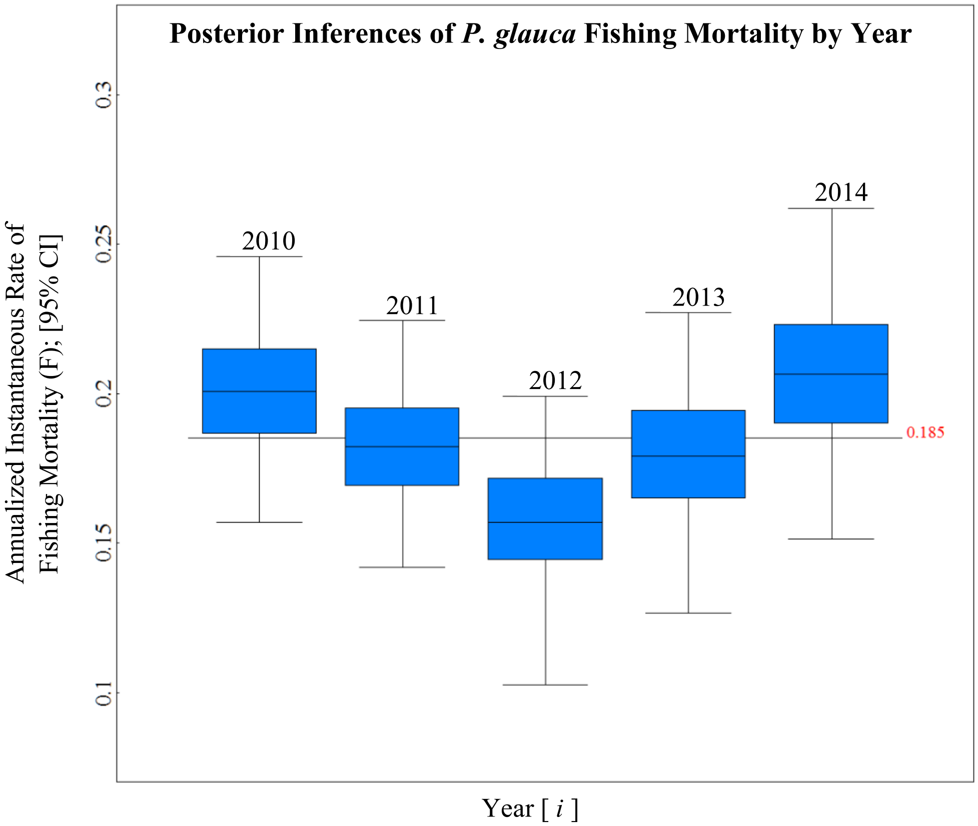


Figure A3–5b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *Prionace glauca* [2010-’14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

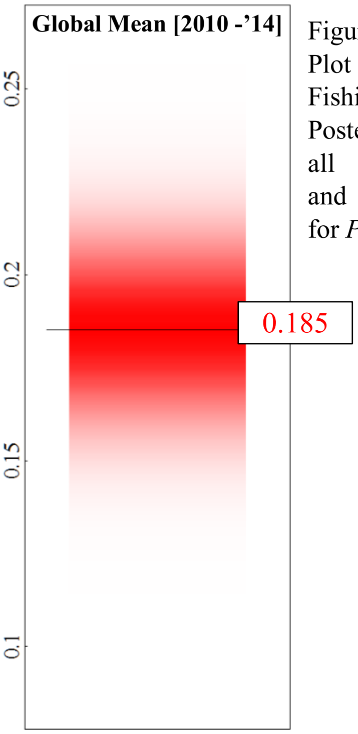
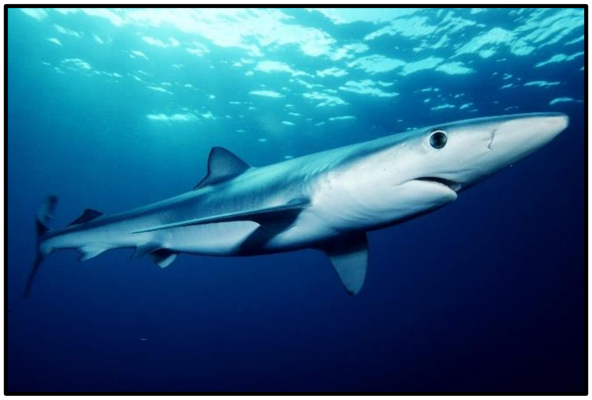


Figure A3–5c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-’14] and for all time-series for *Prionace glauca*.



Blue Shark (*Prionace glauca*) (Conlin, M., 2011, SWFSC)

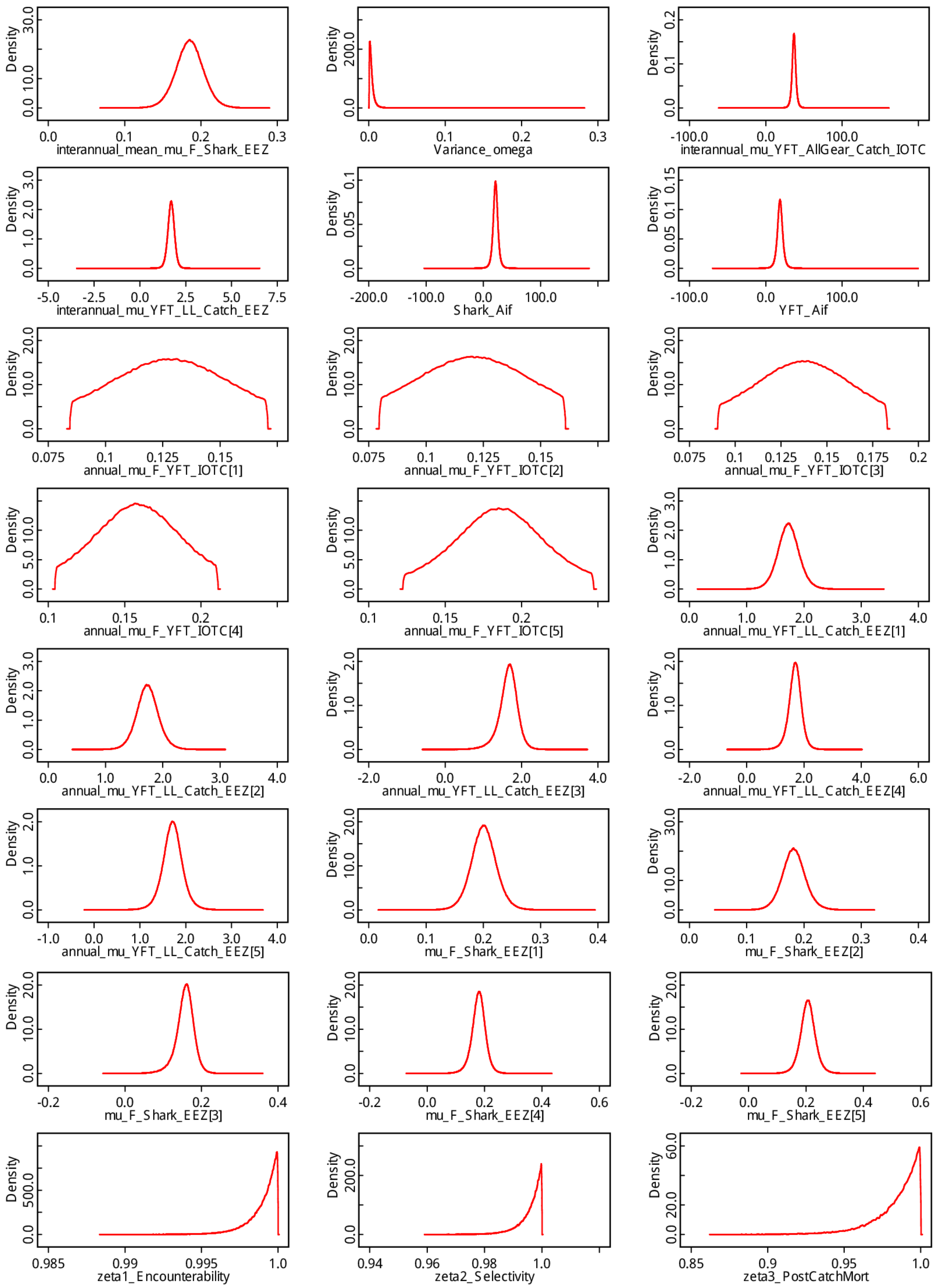


Figure A3–5d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Prionace glauca*.

Table A3–6

Carcharhinus falciformis (Müller & Henle, 1839)
Silky Shark

		mean	*sd*	MC error		C.I. (lower)		median		C.I. (upper)	
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{(i,j)\in I\times J}}$	**0.1928**	2.03E-02	1.28E-04	0.1521	0.1592	0.1672	0.1929	0.2182	0.2257	0.2325
	$\boldsymbol{\sigma}^2_y$	3.74E-03	3.70E-03	8.03E-06	4.85E-04	6.31E-04	8.69E-04	2.74E-03	7.55E-03	1.01E-02	1.30E-02
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (*F or F_i*)	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2010}_{j\in\{1\ldots n\}}}$	0.2090	2.44E-02	1.33E-04	0.1608	0.1693	0.1786	0.2089	0.2394	0.2490	0.2577
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2011}_{j\in\{1\ldots n\}}}$	0.1616	1.96E-02	1.07E-04	0.1231	0.1299	0.1374	0.1614	0.1860	0.1939	0.2012
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2012}_{j\in\{1\ldots n\}}}$	0.1587	2.47E-02	1.18E-04	0.1034	0.1161	0.1285	0.1603	0.1871	0.1952	0.2028
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2013}_{j\in\{1\ldots n\}}}$	0.2056	2.91E-02	1.42E-04	0.1448	0.1573	0.1699	0.2065	0.2403	0.2509	0.2610
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2014}_{j\in\{1\ldots n\}}}$	0.2290	3.12E-02	1.54E-04	0.1667	0.1786	0.1911	0.2290	0.2667	0.2792	0.2915
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}^{AFI_\alpha}_{i\in\{1\ldots n\}}$	299130	66051	73.07	169861	200069	227829	299130	370520	398250	428045
Target (*km2*)	$\boldsymbol{\theta}^{AFI_\beta}_{i\in\{1\ldots n\}}$	549585	133930	146.59	286298	347510	404150	549585	695315	752545	813610
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2010}}$	17260	1974	10.54	13450	14110	14840	17220	19730	20540	21310
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2011}}$	17270	2040	10.39	13340	14030	14780	17230	19830	20680	21470
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2012}}$	16440	2523	11.52	10780	12110	13400	16600	19340	20210	21020
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2013}}$	16790	2345	11.20	11920	12940	13970	16840	19580	20480	21340
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2014}}$	17090	2296	10.99	12560	13450	14350	17070	19870	20830	21770
Post. mean avg. annl. Catch $\mathrm{YFT}^{\mathrm{IOTC}}_{\mathrm{Total}}$&$\mathrm{YFT}^{\mathrm{EEZ}}_{\mathrm{LL}}$('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{IOTC}_{Total}}_{C^{i\in\{1\ldots n\}}}$	369000	31320	32.77	307200	321500	334800	369000	403300	416500	430800
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{i\in\{1\ldots n\}}}$	16970	2020	10.99	13000	13770	14560	16970	19400	20190	20940

(**Cont.**) Table A3–6

Post. means of YFT^{IOTC} Fishing Mortality per yr.											
Inst. rate Fish Mort. (F or F_i)	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2010}}$	0.1280	2.17E-02	2.38E-05	0.0886	0.0920	0.0978	0.1281	0.1580	0.1637	0.1670
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2011}}$	0.1205	2.08E-02	2.27E-05	0.0832	0.0862	0.0916	0.1205	0.1491	0.1544	0.1574
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2012}}$	0.1371	2.28E-02	2.42E-05	0.0951	0.0990	0.1055	0.1372	0.1685	0.1748	0.1785
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2013}}$	0.1582	2.52E-02	2.78E-05	0.1108	0.1157	0.1236	0.1584	0.1927	0.2004	0.2051
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2014}}$	0.1854	2.78E-02	3.00E-05	0.1315	0.1381	0.1477	0.1855	0.2230	0.2324	0.2387
Posterior means of Catch Mechanism Variables											
	$\xi^{Encounterability}$	0.9990	1.00E-03	3.93E-06	0.9963	0.9970	0.9977	0.9993	0.9999	1.0000	1.0000
	$\xi^{Selectivity}$	0.9288	6.06E-02	7.40E-04	0.7761	0.8084	0.8431	0.9447	0.9909	0.9955	0.9978
	$\xi^{Post\text{-}CatchMortality}$	0.9899	9.87E-03	9.88E-05	0.9636	0.9702	0.9770	0.9929	0.9989	0.9995	0.9997

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); ***F$_i$*** [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i***); study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the

Indian EEZ ofexperiencing LL fishing effort ≈ **40.33%**

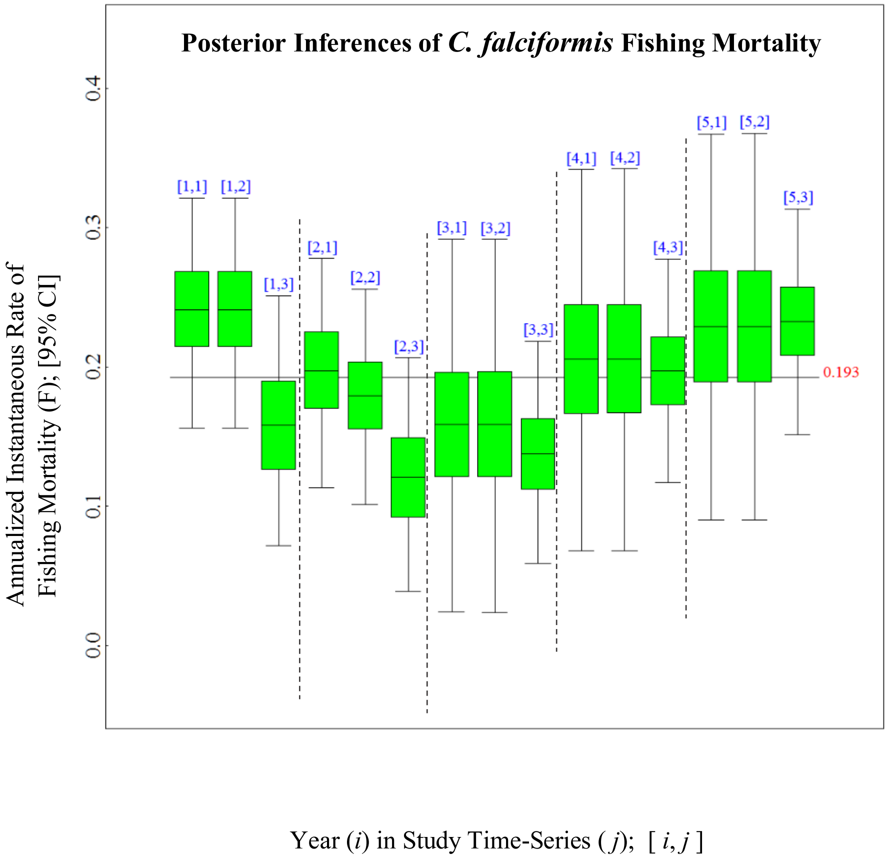


Figure A3–6a. Box Plots of Posterior Inferences of *Carcharhinus falciformis* Fishing Mortality by Year (*i*) and Individual Study Time-series (*j*) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: *i* = 1,...,5 is year 2010,…,2014; *j* = 1 is Abdussamad *et al.* (2012a & 2012b); *j* = 2 is Hornby *et al.*, (2015a & 2015b); *j* = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)].

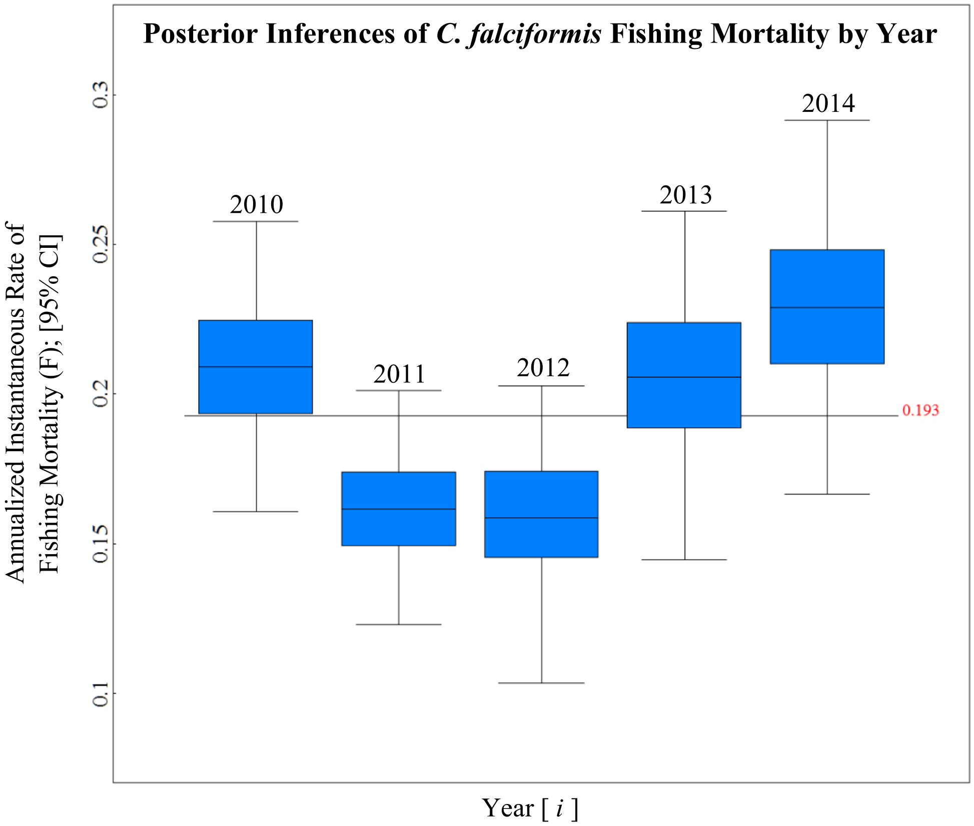


Figure A3–6b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *Carcharhinus falciformis* [2010-'14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

Silky Shark (*C. falciformis*) [Photo: Furlan, B. 1999; (Cuba, Pipin, Jardines de la Reina)] (http://www.fishbase.org/summary/Carcharhinus-falciformis.html)

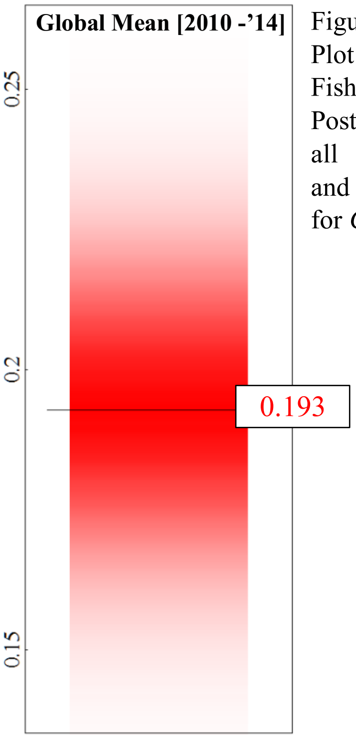


Figure A3–6c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-'14] and for all time-series for *C. falciformis*.

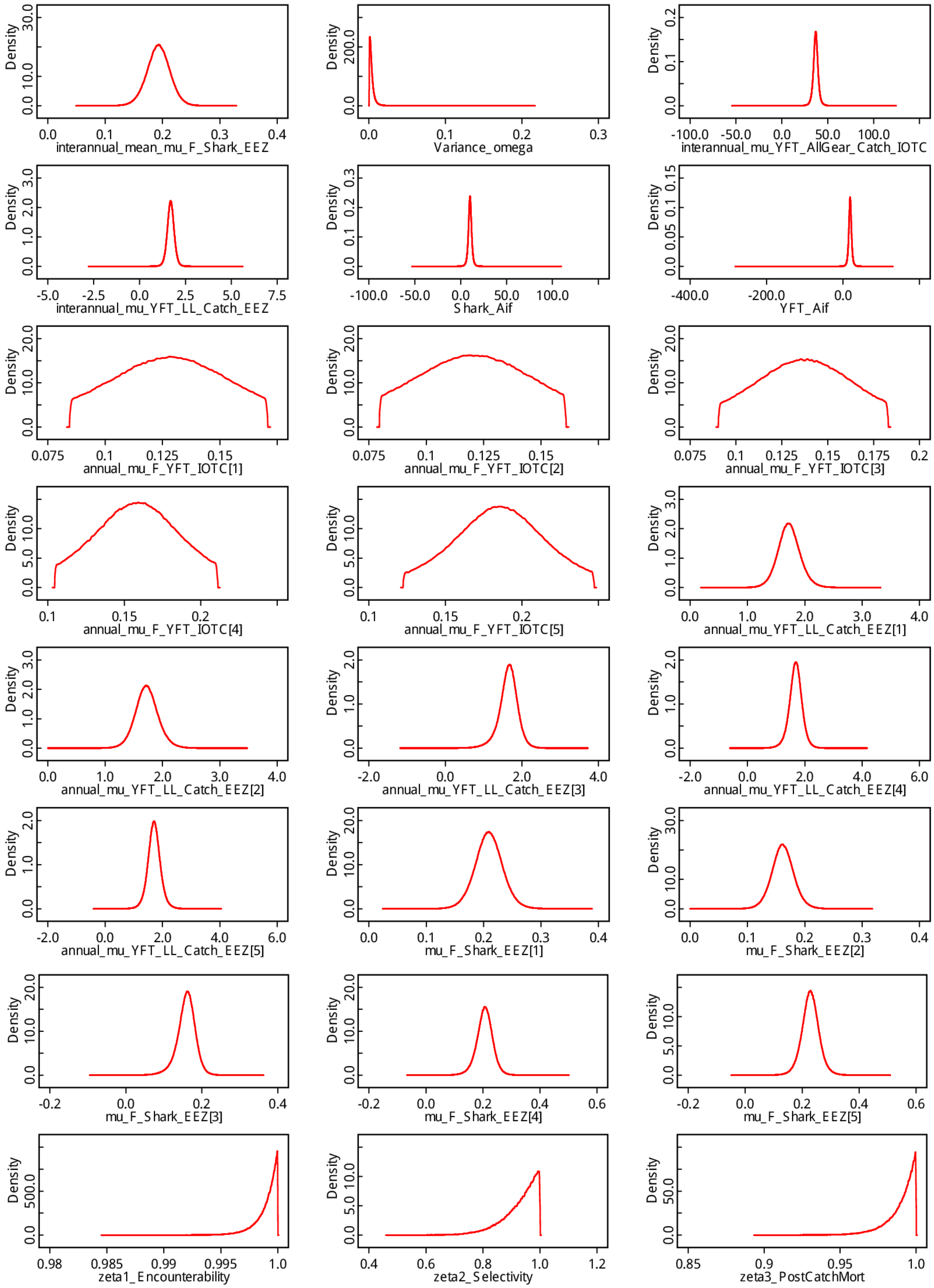


Figure A3–6d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Carcharhinus falciformis*.

Table A3–7

Carcharhinus obscurus (Lesueur, 1818)
Dusky Shark

		mean	*sd*	MC error	C.I. (lower)			median	C.I. (upper)		
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{(i,j)\in I\times J}}$	**0.0479**	1.43E-02	1.03E-04	0.0182	0.0237	0.0299	0.0482	0.0654	0.0709	0.0761
	$\boldsymbol{\sigma}^2_y$	1.02E-03	9.61E-04	2.06E-06	2.38E-04	2.81E-04	3.43E-04	7.52E-04	1.92E-03	2.58E-03	3.38E-03
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (F *or* F_i)	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2010}_{j\in\{1\ldots n\}}}$	0.0538	1.64E-02	1.15E-04	0.0202	0.0264	0.0332	0.0539	0.0739	0.0803	0.0864
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2011}_{j\in\{1\ldots n\}}}$	0.0383	1.19E-02	8.38E-05	0.0143	0.0186	0.0234	0.0383	0.0529	0.0577	0.0622
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2012}_{j\in\{1\ldots n\}}}$	0.0387	1.27E-02	8.40E-05	0.0132	0.0176	0.0227	0.0388	0.0544	0.0594	0.0642
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2013}_{j\in\{1\ldots n\}}}$	0.0604	1.92E-02	1.30E-04	0.0216	0.0285	0.0362	0.0605	0.0841	0.0917	0.0990
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2014}_{j\in\{1\ldots n\}}}$	0.0484	1.55E-02	1.05E-04	0.0174	0.0229	0.0291	0.0484	0.0675	0.0738	0.0798
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}^{AFI_{\alpha}}_{i\in\{1\ldots n\}}$	81568	19001	16.43	44368	53012	61036	81538	102070	110094	118708
Target (*km2*)	$\boldsymbol{\theta}^{AFI_{\beta}}_{i\in\{1\ldots n\}}$	549880	133901	113.99	286180	347805	404445	549880	695315	752545	813610
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2010}}$	17210	2680	13.72	11920	12910	13960	17180	20480	21590	22680
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2011}}$	17230	2696	13.25	11910	12900	13960	17200	20520	21630	22710
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2012}}$	16500	3169	14.16	9717	11210	12690	16620	20160	21330	22490
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2013}}$	16810	3044	14.29	10580	11850	13150	16850	20400	21630	22840
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2014}}$	17060	3059	14.14	10960	12180	13430	17040	20680	21970	23280
Post. mean avg. annl. Catch YFT^{IOTC}_{Total}&YFT^{EEZ}_{LL}('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{IOTC}_{Total}}_{C^{i\in\{1\ldots n\}}}$	369000	31520	27.37	307100	321500	334800	369000	403200	416500	430800
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{i\in\{1\ldots n\}}}$	16960	2695	14.13	11600	12650	13740	16970	20160	21250	22310

(**Cont.**) Table A3–7

Post. means of YFT^{IOTC} Fishing Mortality per yr.											
Inst. rate Fish Mort. $(F \text{ or } F_i)$	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2010}}$	0.1280	2.17E-02	1.88E-05	0.0886	0.0920	0.0978	0.1281	0.1580	0.1637	0.1670
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2011}}$	0.1205	2.07E-02	1.75E-05	0.0832	0.0863	0.0917	0.1205	0.1491	0.1544	0.1573
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2012}}$	0.1370	2.28E-02	1.96E-05	0.0951	0.0990	0.1054	0.1371	0.1685	0.1748	0.1785
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2013}}$	0.1583	2.52E-02	2.19E-05	0.1107	0.1157	0.1236	0.1584	0.1928	0.2004	0.2051
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2014}}$	0.1854	2.78E-02	2.36E-05	0.1314	0.1380	0.1477	0.1856	0.2230	0.2324	0.2386
Posterior means of Catch Mechanism Variables											
	$\xi^{Encounterability}$	0.9990	9.95E-04	2.81E-06	0.9963	0.9970	0.9977	0.9993	0.9999	0.9999	1.0000
	$\xi^{Selectivity}$	0.2405	7.93E-02	6.71E-04	0.0888	0.1153	0.1445	0.2373	0.3394	0.3747	0.4084
	$\xi^{Post\text{-}Catch Mortality}$	0.9737	2.54E-02	2.20E-04	0.9061	0.9226	0.9396	0.9814	0.9972	0.9986	0.9993

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); ***F**$_i$* [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i***); study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the Indian EEZ ofexperiencing LL fishing effort ≈ **40.41%**

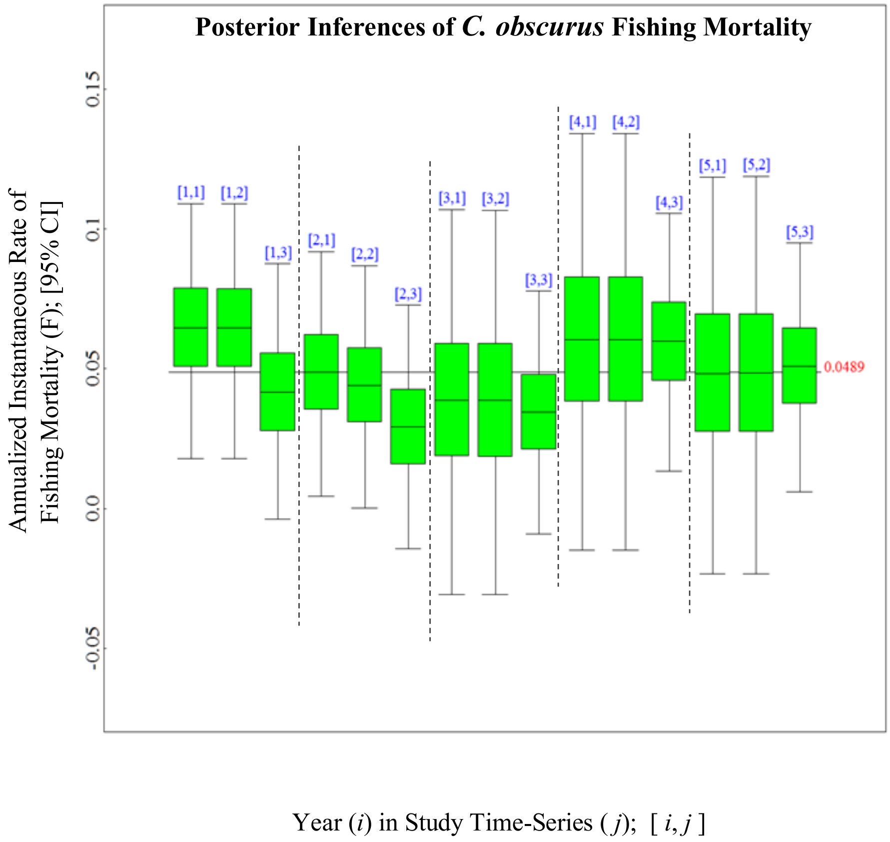


Figure A3–7a. Box Plots of Posterior Inferences of *C. obscurus* Fishing Mortality by Year (*i*) and Individual Study Time-series (*j*) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: *i* = 1,...,5 is year 2010,…,2014; *j* = 1 is Abdussamad *et al.* (2012a & 2012b); *j* = 2 is Hornby *et al.*, (2015a & 2015b); *j* = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)].

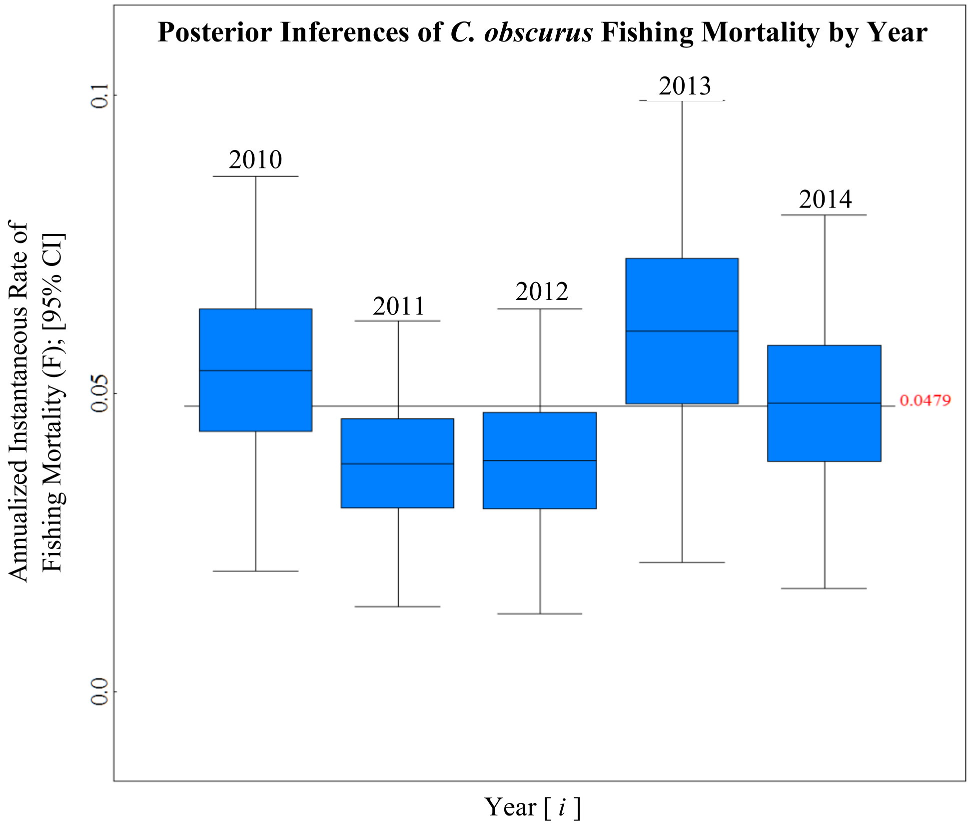


Figure A3–7b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *Carcharhinus obscurus* [2010-'14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

Dusky Shark (*C. obscurus*) (Photo: Murch, A., 2016, (Gulf of Mexico. Venice, Louisiana)] (http://www.elasmodiver.com)

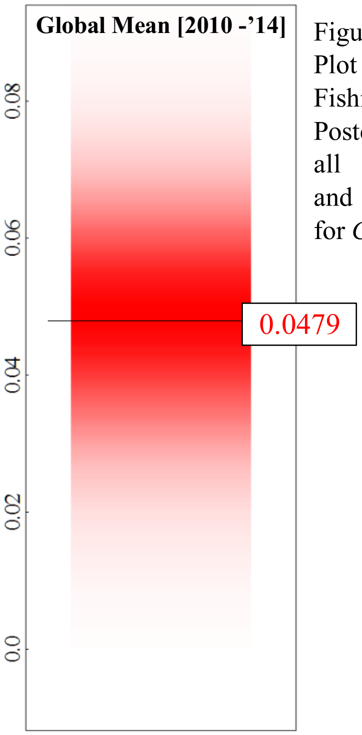


Figure A3–7c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-'14] and for all time-series for *C. obscurus*.

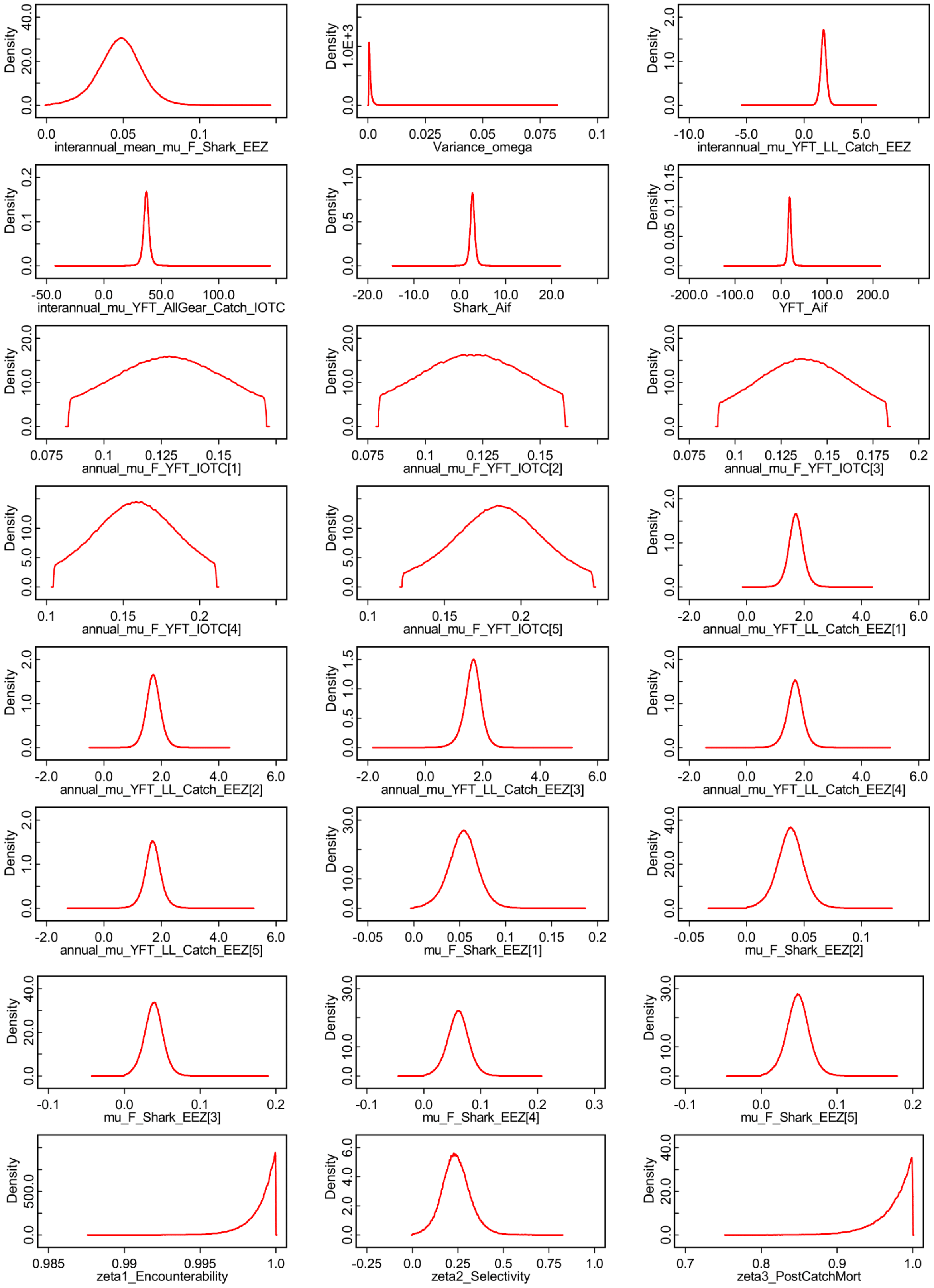


Figure A3–7d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Carcharhinus obscurus*.

Table A3–8

Stegostoma fasciatum (Hermann, 1783)
Zerba Shark

		mean	*sd*	MC error		C.I. (lower)		median		C.I. (upper)	
					2.5%	5.0%	10%		90%	95%	97.5%
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{(i,j)\in I\times J}}$	**0.1113**	2.39E-02	1.16E-04	0.0613	0.0714	0.0818	0.1118	0.1402	0.1491	0.1575
	$\boldsymbol{\sigma}^2_y$	2.77E-03	2.85E-03	5.72E-06	4.19E-04	5.30E-04	7.04E-04	1.99E-03	5.56E-03	7.52E-03	9.86E-03
Post. mean of Shark spp. Fishing Mortality in yr. i											
Inst. rate Fish Mort. (*F or F_i*)	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2010}_{j\in\{1\ldots n\}}}$	17670	2684	12.42	12640	13510	14460	17550	21000	22210	23400
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2011}_{j\in\{1\ldots n\}}}$	17110	2636	12.72	11940	12870	13890	17080	20350	21430	22490
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2012}_{j\in\{1\ldots n\}}}$	16410	3173	13.54	9557	11070	12560	16550	20080	21250	22410
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2013}_{j\in\{1\ldots n\}}}$	16840	2996	13.29	10760	11970	13220	16860	20410	21630	22840
	$\boldsymbol{\mu}^{Shark^{EEZ}_{LL}}_{F^{2014}_{j\in\{1\ldots n\}}}$	16940	3019	13.28	10860	12060	13320	16940	20530	21780	23020
Effective Area of Fishing Impact Posterior mean											
Shark (*km2*)	$\boldsymbol{\theta}^{AFI_{\alpha}}_{i\in\{1\ldots n\}}$	369000	31520	27.06	307300	321500	334900	369000	403200	416600	431000
Target (*km2*)	$\boldsymbol{\theta}^{AFI_{\beta}}_{i\in\{1\ldots n\}}$	16990	2673	13.19	11760	12760	13820	16970	20170	21270	22380
Post. means of Oceanic EEZ Tuna Catch per yr.											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2010}}$	17670	2684	12.42	12640	13510	14460	17550	21000	22210	23400
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2011}}$	17110	2636	12.72	11940	12870	13890	17080	20350	21430	22490
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2012}}$	16410	3173	13.54	9557	11070	12560	16550	20080	21250	22410
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2013}}$	16840	2996	13.29	10760	11970	13220	16860	20410	21630	22840
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{2014}}$	16940	3019	13.28	10860	12060	13320	16940	20530	21780	23020
Post. mean avg. annl. Catch YFT$^{IOTC}_{Total}$&YFT$^{EEZ}_{LL}$('10-'14)											
(*Tonnes*)	$\boldsymbol{\mu}^{Tuna^{IOTC}_{Total}}_{C^{i\in\{1\ldots n\}}}$	369000	31520	27.06	307300	321500	334900	369000	403200	416600	431000
	$\boldsymbol{\mu}^{Tuna^{EEZ}_{LL}}_{C^{i\in\{1\ldots n\}}}$	16990	2673	13.19	11760	12760	13820	16970	20170	21270	22380

(**Cont.**) Table A3–8

Post. means of YFT^{IOTC} Fishing Mortality per yr.											
Inst. rate Fish Mort. (F *or* F_i)	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2010}}$	0.1280	2.17E-02	1.83E-05	0.0886	0.0920	0.0979	0.1281	0.1579	0.1636	0.1670
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2011}}$	0.1205	2.07E-02	1.82E-05	0.0832	0.0863	0.0916	0.1205	0.1491	0.1544	0.1574
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2012}}$	0.1371	2.29E-02	1.96E-05	0.0951	0.0990	0.1054	0.1371	0.1685	0.1748	0.1785
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2013}}$	0.1582	2.52E-02	2.15E-05	0.1107	0.1157	0.1235	0.1583	0.1927	0.2003	0.2051
	$\mu^{Tuna^{IOTC}_{Total}}_{F^{2014}}$	0.1854	2.78E-02	2.41E-05	0.1314	0.1380	0.1477	0.1856	0.2230	0.2324	0.2387
Posterior means of Catch Mechanism Variables											
$\xi^{Encounterability}$		0.7024	1.69E-01	9.21E-04	0.3705	0.4198	0.4765	0.7081	0.9264	0.9600	0.9783
$\xi^{Selectivity}$		0.8197	1.54E-01	8.49E-04	0.4654	0.5211	0.5911	0.8585	0.9863	0.9945	0.9977
$\xi^{Post\text{-}CatchMortality}$		0.8631	1.32E-01	6.86E-04	0.5309	0.5918	0.6662	0.9058	0.9914	0.9965	0.9985

AFI (Area of Fishing Impact); ***C*** (Catch); **C.I.** [Credible Interval (Bayesian equivalent of Confidence Interval)]; **EEZ** [Exclusive Economic Zone (India)]; ***F*** (Instantaneous Rate of Fishing Mortality); ***F_i*** [Instantaneous Rate of Fishing Mortality, species/category (**i**); not to be confused with year index ***i***]; ***LL*** (Long-line); **MC Error** (Monte Carlo Error); ***sd*** (standard deviation); **IOTC** (Indian Ocean Tuna Commission); **YFT** (Yellowfin Tuna); year index (***i***); study/times series index (***j***)

% Core Effective habitat within the oceanic domain of the Indian EEZ ofexperiencing LL fishing effort ≈ **46.37%**

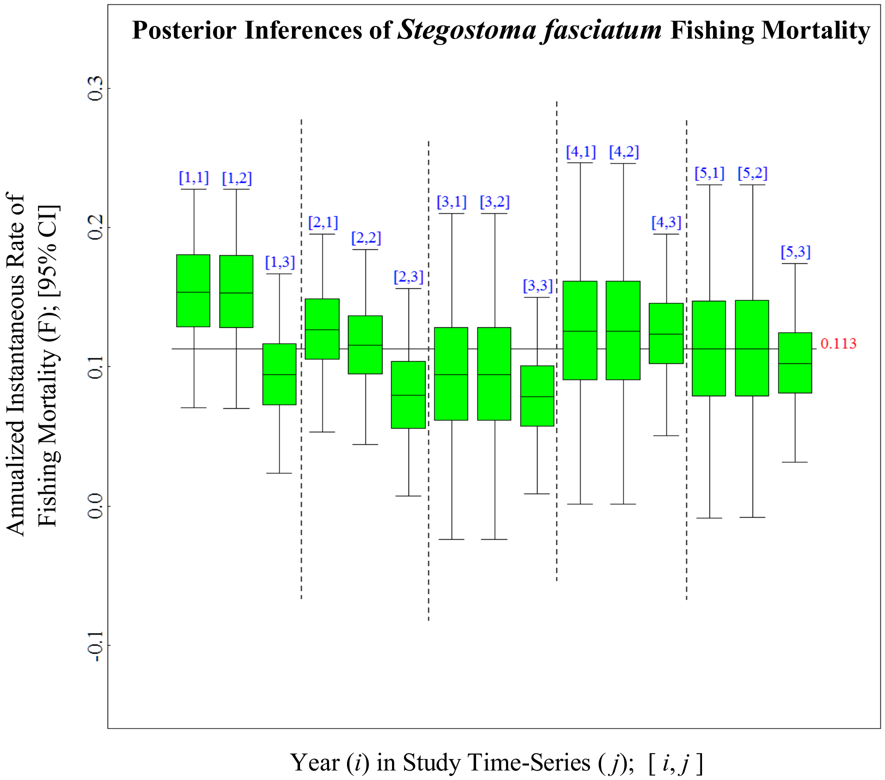


Figure A3–8a. Box Plots of Posterior Inferences of *Stegostoma fasciatum* Fishing Mortality by Year (*i*) and Individual Study Time-series (*j*) [2010-'14]. Dotted-lines organize groups of inferences in relation to their corresponding applicable year of output, and not by any data-set affiliation. [Indices: *i* = 1,...,5 is year 2010,…,2014; *j* = 1 is Abdussamad *et al.* (2012a & 2012b); *j* = 2 is Hornby *et al.*, (2015a & 2015b); *j* = 3 is *India's National Reports to the Scientific Committee of the IOTC* by the Fisheries Survey of India (Various Authors, 2010-2015)].

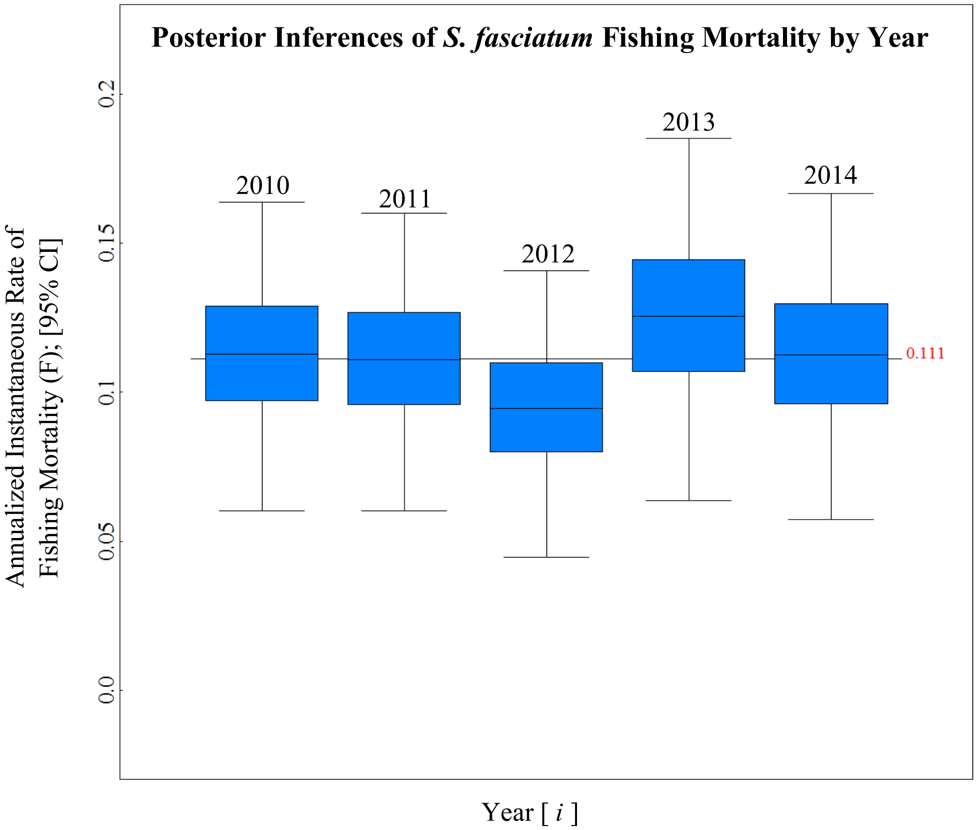


Figure A3–8b. Box Plots of Posterior Inferences of Mean Year-wise Fishing Mortality for *Stegostoma fasciatum* [2010-'14]; [*i* = 1 is 2010, *i* = 2 is 2011, etc.].

Zebra Shark (*Stegostoma fasciatum*) [Photo: Krajangdara, T., 2004; (Thailand, Andaman Sea; Fisheries Research Vessel-Pramong 4)] (http://www.fishbase.se/photos/UploadedBy.php?autoctr=14238&win=uploaded)

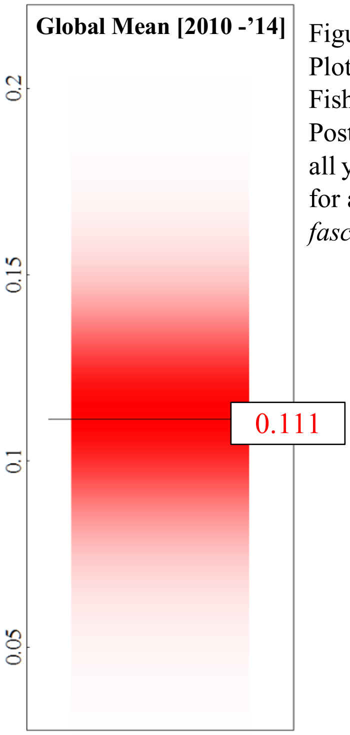


Figure A3–8c. Density Plot of Global Mean of Fishing Mortality Posterior Means over all years [2010-'14] and for all time-series for *S. fasciatum.*

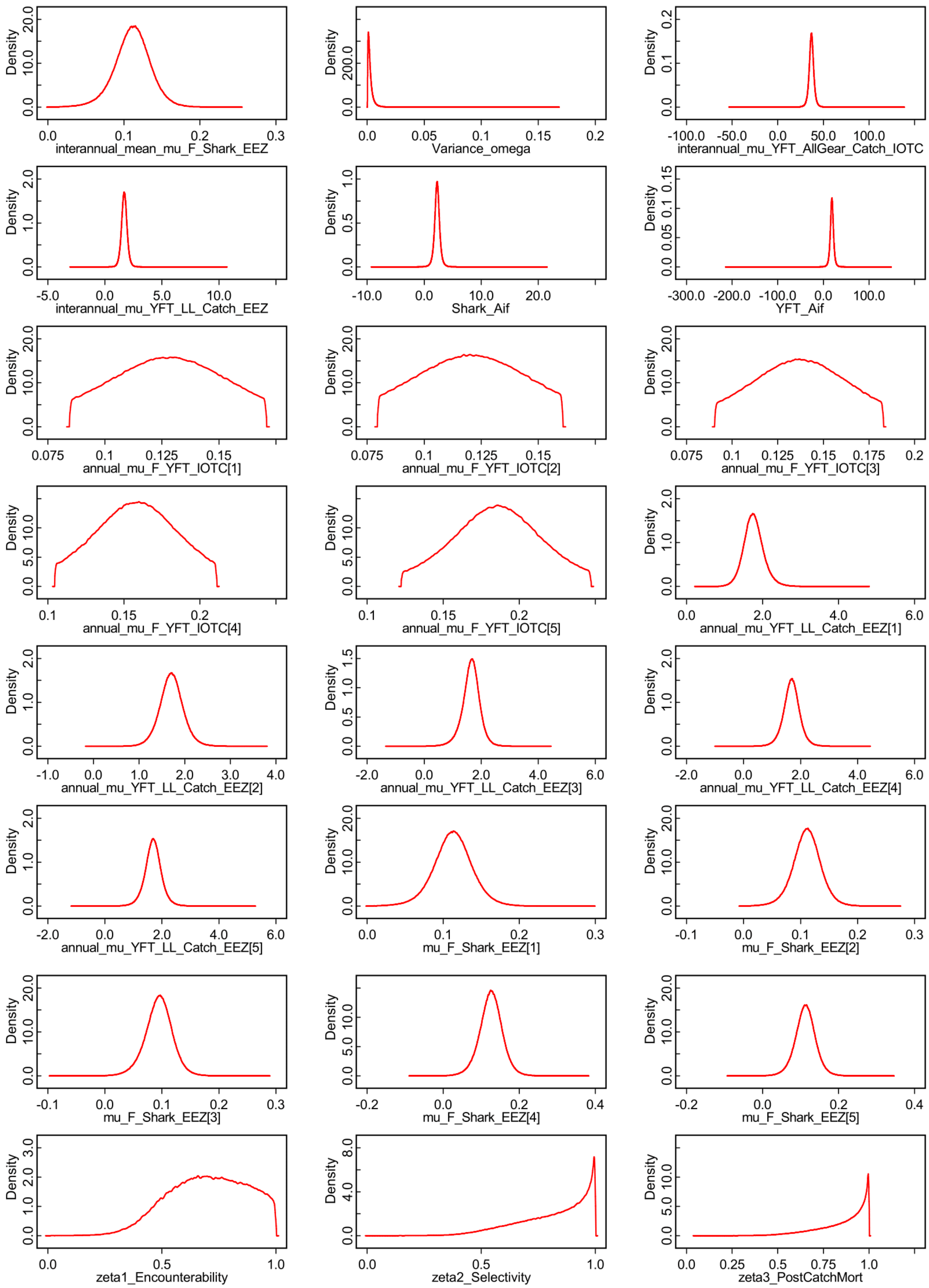


Figure A3–8d. Kernel Density Estimates of Posterior Probability Density Functions for Selected Equation Variables for *Stegostoma fasciatum*.