Ecological risk assessment of the Marshall Islands longline tuna fishery

Eric Gilmana, b, Matthew Owensb, c, Thomas Kraftc

a Hawaii Pacific University, Department of Natural Resources, 3661 Loulu Street, Honolulu, HI 96822, USA
b FishWise, Box 233, Santa Cruz, CA, USA
c Norpac Fisheries Export, 3125 Eastlake Ave. E., Seattle, USA

ABSTRACT

To support implementing an ecosystem approach to fisheries management, ecological risk assessment (ERA) methods have recently been developed for the continuum of data-deficient to data-rich fisheries. A semi-quantitative ERA was conducted for the Marshall Islands longline bigeye tuna (Thunnus obesus) fishery. The study used information from analyses of observer data, surveys of captains and crew and inventories of gear and equipment. Relative risks were evaluated through a consideration of phylogenetic uniqueness, risk of population extirpation, risk of species extinction and importance in ecosystem regulation. The fishery presents a highest relative risk to leatherback (Dermochelys coriacea), hawksbill (Eretmochelys imbricata), green (Chelonia mydas) and olive Ridley (Lepidochelys olivacea) sea turtle Regional Management Units that overlap with the fishery, in that order. The next highest relative risk is to affected stocks of oceanic whitetip (Carcharhinus longimanus), blue (Prionace glauca), and silky (Carcharhinus falciformis) sharks, in that sequence. Seabird bycatch is likely not problematic. There was inadequate information to assess risks to cetacean populations. Risks to stocks of market and non-market species of marine fishes with r-selected life history characteristics were not assessed. This is because estimates of critical threshold levels of local and absolute abundance and current biomass are not known for many of these stocks. Several best practice gear technology methods to mitigate problematic catch of vulnerable species groups are currently employed: monofilament leaders, whole fish for bait, single-hooking fish bait, no lightsticks, and no fishing at shallow submerged features. Setting terminal tackle below 100 m and carrying and using best practice handling and release equipment were methods identified to reduce fishing mortality and injury of vulnerable species. More information is needed to determine if weaker hooks should be prescribed to mitigate cetacean bycatch. The large benefit to sea turtles of replacing remaining J-shaped hooks with circle hooks might outweigh a possible small increase in elasmobranch catch rates. The consumption of 2024 l of fuel per tonne of landed catch, which is within the range of available estimated rates from similar fisheries, could be reduced, reducing greenhouse gas emissions, through more frequent maintenance and upgrading vessel equipment and materials. Observer data quality may be adequate to support a quantitative Level 3 ERA to determine the significance of the effect of various factors on standardized catch rates and to estimate population-level effects from fishing mortality.

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1. Introduction

To contribute to implementing an ecosystem approach to fisheries, methods for ecological risk assessment (ERA) of the effects of capture fisheries have recently been developed for the continuum of data-deficient to data-rich fisheries, including rapid first order evaluations, semi-quantitative assessment, and quantitative assessments with large data requirements. The objective of analysis of fisheries ERAs have largely been to determine population- and species-level relative risks from fishing mortality of individual groups of associated and dependent species relatively vulnerable to fisheries overexploitation, implemented through productivity-susceptibility analyses (PSA). Fisheries ERAs have also assessed absolute population- and species-level effects from fishing mortality, and risks from direct contact by bottomfish fishing gear with benthic vulnerable marine ecosystems [1–3]. Most ERAs have not assessed relative risks from fishing operations across affected taxonomic groups, risks at other levels of marine biodiversity including effects on genetic diversity and evolutionary processes resulting from selective fishery removals and broad community- and ecosystem-level effects, nor assess risks from collateral effects of fishing operations [1,4].
In the early 2000s, the Commonwealth Scientific and Industrial Research Organization (CSIRO) developed a fisheries ERA method for the Australian national fisheries management authority to assess the direct population-level effects of fishing [5]. The CSIRO method is intended to employ three progressive levels along a continuum from a qualitative first order to quantitative rigorous assessment [1–3,5–10]. Level 1 and 2 assessments are useful mainly for rapid first order evaluations and where there are data deficiencies with the fishery or species being assessed [6,8]. Under the CSIRO method, as adapted by others, fishery ERA is intended to move from Level 1 to 3 progressively with subsequent levels focusing on species identified from the lower-level less rigorous assessments as being of high risk [5,6]. Thus, the less rigorous risk assessments can also be useful to assess large numbers of populations to triage those deemed to be relatively vulnerable to undergo more rigorous population analysis to determine the risk of extirpation [11].

Level 1 involves a qualitative assessment based on expert opinion. For example, CSIRO and the Marine Stewardship Council (MSC) use a qualitative method called 'Scale, Intensity, Consequence' analysis (SICA) for Level 1 ERAs of data-deficient fisheries. SICA employs expert judgment to identify the worst plausible scenarios for impacts of the fishery, identify the degree of spatial and temporal overlap between the stock or habitat and fishing activity, estimate the degree of intensity of fishing activities that adversely impact stocks, habitat and ecosystem integrity, and identify the consequences of fishing activities on population viability, habitat integrity, and ecosystem integrity [1,8].

Level 2 is a semi-quantitative assessment. Productivity-susceptibility analysis (PSA) is a common approach for Level 2 semi-quantitative fisheries ERA. In a PSA, assessment of productivity considers intrinsic factors such as demographic characteristics such as growth rate, longevity, fecundity, recruitment, and natural mortality, which influence the intrinsic rate of increase ($r$, natural growth rate of a population) in the absence of fishing mortality, which is an indicator of a population's relative resistance to fishing mortality and resilience or ability to recover from depletion. Susceptibility considers extrinsic factors that influence the level of fishing mortality, including whether a population overlaps with the fishery temporally and spatially, what proportion of each age class overlaps with the fishery, the probability of a fishery interaction, and the probability of capture, injury and mortality as a result of a fishery interaction. PSAs have largely been applied to compare relative risks of a fishery on the viability of assessed populations [1,3,12–15]. PSAs have also been applied to assess relative risk of causing overexploitation of fish stocks [16].

Finally, Level 3 quantitative assessments, which have relatively large data requirements, employ model-based analyses to document absolute population-level effects and assess extirpation risk of populations of marine species from fishing mortality [1,6–7,9,11]. There have been numerous analytical methods used in Level 3 ERAs, with varying degrees of data requirements and certainty in outcomes [1,11,17–27]. To provide robust outputs, these methods require accurate estimates of total fishery removals (observable and cryptic sources) by age class and sex, knowledge of which populations these removals are from, time series of population abundance, population maximum growth rate and capacity to recover once depleted, other key life-history characteristics (including age at maturity, body growth rate, natural mortality), and estimates of a limit fishing mortality rate that will lead to population extirpation (e.g., $E_{frash}$) and minimum viable population size (e.g., $B_{crit}$) [4,11,23,24,28]. Due to large gaps in understanding of life histories for many marine species, information on total cumulative anthropogenic levels of removals from an individual population, knowledge of the conservation status from individual populations, and deficits in monitoring, including in data collection protocols, observer coverage rates, and sufficient time-series to detect the response in absolute population abundance of long-lived species to this anthropogenic mortality source, in most fisheries [2–3,24,29,30], data requirements for robust Level 3 ERAs are often not able to be met.

Pelagic fisheries ERAs have largely assessed the relative risks of fisheries on populations of species relatively vulnerable to fisheries overexploitation, including bycatch of seabirds, sea turtles, marine mammals and elasmobranchs [2,12–15,31]. There has been limited assessment or accounting for broad community- and ecosystem-level risks from fishing operations in tuna and other fisheries [2,32]. This deficit is likely partly linked to the limited state of understanding of broader community- and ecosystem-level effects from fishing operations, and a lack of agreed guidance on best practices for management authorities to monitor, estimate, and account for these broader effects [2].

Mitigating the fishing mortality of species that are relatively vulnerable to extinction due to their life history characteristics and susceptibility to capture and mortality in fisheries, one component of an ecosystem approach to fisheries management, has received substantial international attention since the late 1990s [2,33–36]. Legal instruments establishing international responsibility to conserve associated and dependent species, species that belong to the same ecosystem or are associated with or dependent on market species removed by fisheries, are relatively recent, first becoming an obligation under the 1982 Law of the Sea Convention, and elaborated further in subsequent bilateral organizations’ instruments and guidance [2,37,38]. At the species- and population-levels of biodiversity, there is documentation of few contemporary marine species extinctions (c. 39 in the past 300 years), with an order of magnitude higher number of documented contemporary population extirpations due primarily to overexploitation and habitat degradation, in part, from marine fisheries. However, it is hypothesized that these numbers are underestimated due to difficulties in detecting extirpation and extinction of populations and species of non-air-breathing marine organisms and due to uncertainty in taxonomic status [30,39–41]. Population extirpations represent the permanent loss of unique genotypes, and can reduce species resilience and concomitant resistance to extinction, as well as cause broad changes in community structure and functioning [30,39,40].

Populations of marine species with a K-selected life-history strategy (characterized by long lifespan, slow growth, late sexual maturity, low fecundity, and low natural mortality rates of sub-adult and adult age classes) can decline over short temporal scales (decades and shorter) and are slow to recover from large declines [24,29,42–45]. However, populations of highly fecund r-selected marine species and those with broad distributions (common, widespread generalists) can be extirpated due to anthropogenic stressors, including fishing mortality [11,30,46].

Seabirds, sea turtles, marine mammals and elasmobranchs can be captured in longline tuna fisheries [32]. A range of effective and commercially viable methods to mitigate problematic bycatch of these taxonomic groups in longline tuna fisheries has been developed, although there has been mixed progress in uptake of these best practices by domestic management systems and regional fisheries management organizations [2,32,37,47]. Cryptic, largely undetectable, mortality in longline fisheries occurs, for instance, through pre-catch, post-release and ghost fishing mortalities [4]. Pelagic longline fisheries likely have nominal habitat effects.

Contact between soaking pelagic longline gear and the seabed can occur in fisheries that make sets at shallow submerged features [48,49], and currents might bring lost, abandoned and discarded longline gear into contact with sensitive habitats [50]. Collateral, indirect effects of pelagic longline fisheries are not well understood, have not been within the scope of risk assessments, and are largely not accounted for by management authorities [2,4,51].
These include, for example, altered pelagic trophic structure and processes, where the selective removal of older age classes of a subset of species of a pelagic ecosystem apex predator guild has cascading effects up and down the pelagic ecosystem food web. For example, pelagic longline selective removal of apex predators has resulted in a top-down trophic effect by releasing pressure and increasing abundance of mid-trophic level species, altered the ecosystem size structure with a decline in abundance of large-sized species of fish and increase in abundance of smaller-sized species, and may have altered the length frequency distribution of populations subject to fishing mortality [49,52–57]. The selective removal of some species from the pelagic ecosystem apex predators guild may alter the relative abundance of species within this trophic level, while the selective removal of large individuals could be a driver favoring genotypes for maturation at an earlier age, smaller-size and slow-growth, potentially altering the length frequency distributions and evolutionary characteristics of affected populations [49,58]. Or, for example, reducing the abundance of tunas by fishing reduces the availability of prey to seabirds because tunas and possibly other pelagic apex predators bring baitfish to the surface [59,60]. By reducing optimal school sizes, longline fisheries might reduce the fitness of individuals of a school that has lost members to longline catch, including by increasing predation risk, but also reducing efficiency in foraging and energy expenditure [46,62]. As a final example, the disposal of sea offal, spent bait and dead catch can change foraging behavior, diet, competition amongst coastal and marine species, and community composition [63]. For discharges occurring in deep regions, large proportions of discharges may settle through the water column without being consumed. This could alter the benthic community, and transfer biomass to bottom currents for centuries before recycling to the pelagic ecosystem [4,44]. An additional collaterel effect, capture fisheries are also highly dependent on fossil fuels, posing a risk to their economic viability with steadily rising fuel costs, and are a substantial source of greenhouse gas emissions, contributing to global climate change [64,65].

A mixed-level semi-quantitative fisheries ERA was conducted for the Republic of the Marshall Islands longline bigeye tuna (Thunnus obesus) fishery, which fishes primarily at grounds within the Marshall Islands exclusive economic zone (EEZ). Study aims were to identify: (i) relative risks to population viability of associated and dependent species; (ii) opportunities to mitigate identified problematic bycatch through gear technology methods, involving catches in fishing gear and methods; and (iii) opportunities to improve vessel fuel efficiency, lowering fuel costs and greenhouse gas emissions. Using the CSIRO fishery ERA categorization scheme, this study constituted a Level 1 ERA by employing qualitative information from surveys of participants in the capture sector, and a partial Level 2 ERA through assessing susceptibility through a combination of available quantitative (gear inventory, amalgamated observer data, conservation status of affected vulnerable stocks and populations, relative phylogenetic uniqueness, relative role in ecosystem regulation) and qualitative (survey of captains and crew) data sources. Susceptibility was assessed through a combination of: (i) an inventory of fishing gear and assessment of the risk to vulnerable species based on knowledge of the effects of different gear designs on species-specific catch rates; (ii) interviews with vessel operators and crew; and (iii) information from studies that analyzed observer program data and summary statistics from amalgamated observer program data from the fishery, documenting catch rates, levels and disposition of vulnerable species upon release. Given the high uncertainty in estimates of bycatch levels and rates and lack of age- or length-specific data, the poor data quality did not support assessing population-level effects. However, the conservation status of affected stocks of shark species and populations of sea turtles captured in the fishery are identified and discussed to support understanding the relative risks posed by the fishery.

2 Methods

From 22–26 November 2012, captains and crew were interviewed and an inventory of equipment and gear was conducted for 15% (8 of 55) of vessels of the Marshall Islands pelagic longline bigeye tuna fishery.2 Vessels were selected for inclusion in the study based on their being in port during the period when the surveys and inventories were conducted. The selection of information to be collected on fishing gear and methods was based on evidence of the significant effect of these factors on bycatch rates of species groups known to be vulnerable to overexploitation in pelagic longline fisheries [32,49,67,68]. Hook measurements (width at narrowest position and wire diameter) were made using calipers with 1 mm intervals. Information collected to identify opportunities for improving fuel efficiency was selected from a review of Suuronen et al. [64] and from consultations with fishery development expert Steve Beverly, a retired longline fisher and fishery development officer with the Secretariat of the Pacific Community. Through the dockside inventory and interviews, information on gear designs, fishing methods, catch composition, catch retention and discarding practices for market and non-market species, and vessel characteristics and equipment that affect fuel consumption were obtained.

Information was also obtained from a review of previous studies that analyzed observer program data and summary statistics and amalgamations of observer program data, providing somewhat dated information on catch rates, levels, and disposition of vulnerable species (onboard observer coverage last occurred in the fishery in 2009, MIMRA [66]). This information contributed to identifying relative and absolute risks and provided an independent source of information to validate the social survey results. Information collected through the inventory of vessel gear was not available through available amalgamated observer data, but some information on past gear designs was available in the literature. Data on fuel consumption and retained/landed catch was obtained from Luen Thai Fishing Venture company records.

Information on the known conservation status of populations of sea turtles and stocks of sharks identified as being captured in the fishery was also compiled. Information on conservation status (relative risk scores) of relevant Regional Management Units (RMUs) per Wallace et al. [69] were used for sea turtles. For elasmobranchs, available stock assessment reports were reviewed, which existed for blue (Prionace glauca), silky (Carcharhinus falciformis) and oceanic whitetip (Carcharhinus longimanus) stocks that overlap with the Marshall Islands longline fishery [70–72]. The IUCN Red List categorizations of sea turtle and shark species documented as captured in the fishery were also identified.

Three criteria were used to estimate relative risks within and between taxonomic groups. The first criterion is a comparison of the category of threat status assigned to the individual affected populations (populations that interact with the fishery) and global species-wide conservation status, or otherwise of sea turtle RMU conservation status as defined by Wallace et al. [69]. The second criterion compares the phylogenetic uniqueness of affected species; phylogenetically distinct species are of relative importance for the potential continuation of evolutionary processes because they lack or have few close taxonomic relatives and have relatively distinct genetic diversity [73]. PD50 indices for a species were employed, which is the expected phylogenetic diversity (PD) loss if the species goes extinct, assuming all other species have a 50% probability of persistence [73,74]. The third criterion, assesses

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2 There were 55 longline vessels licensed to fish in the Marshall Islands Exclusive Economic Zone (EEZ) in 2011, of which 39 were domestically-based [66]. All domestically-based vessels were owned and managed by a single company, Luen Thai Fishing Venture.
relative importance of the role of a species affected by a fishery in maintaining ecosystem resistance and resilience by regulating structure and processes (keystone and foundation species/guilds) [30]. If available, the ERA method was to account for the level of fishing mortality on affected taxa and age classes and sex ratios of removals. The relative risk assessment was conducted only for sea turtle RMUs and three elasmobranch stocks included in this ERA. A lack of information on both the species and populations of seabirds and marine mammals affected by the fishery precluded their inclusion in the assessment of cross-taxa relative risk. Furthermore, stocks of market (target and incidental) and non-market (discarded) selected fish species were excluded from the assessment. This decision was based on: (i) a lack of information on the risk of these stocks exceeding threshold minimum viable population sizes and fishing mortality rates beyond which irreversible damage and extirpation occurs; (ii) a lack of understanding of the risk of exceeding stock-level thresholds beyond which there is protracted or permanent alteration to their roles in ecosystem regulation (see Discussion Section 4.6); and (iii) the assumption that due to these species’ high productivity, they have a substantial lower risk of population extirpation relative to the included K-selected species, an initial assessment activity typically taken in Level 1 fisheries ERAs [1].

3. Results
3.1. Fishing gear, methods, catch composition, disposition, catch rates and levels, retention and, discard practices, and fuel efficiency

Tables 1 and 2 provide summary statistics from data obtained from the survey and vessel inventory. The eight interviewees have been longline fishing for an average of 30 years, fished from Majuro for an average of 6 years, and served on the current vessel for an average of 3 years. Seven of those surveyed were vessel captains, one was a first mate. Based on the survey responses, the fleet fishes throughout the year, vessels make an average of 13 sets per trip and 22 trips per year. Each trip lasts about 19 days.

Based on the vessel inventory, three hook types were included in the gear. The majority of hooks were 14/0 10 degree offset circle ring hooks with a diameter of 3.7 cm at its narrowest width and 5 mm wire diameter, manufactured by the Chinese company Ningbo Jessn Ocean Exploitation (part number AYA010020), followed by a 15/0 10 degree offset circle ring hook with a diameter of 4.0 cm at its narrowest width and 5 mm wire diameter also manufactured by Jessn (part number AYA010008). A small proportion of hooks were 10 degree offset tuna ring hooks with a diameter of 3.2 cm at its narrowest width and 5 mm wire diameter (manufacturer not known, possibly a Tankichi offset 3.6 sun tuna hook: (i) a metal clip attaching the branchline to the mainline; (b) unweighted swivel; (c) 2 m nylon rope; (d) 20 m clear 1.8 mm diameter monofilament line crimped onto the nylon rope; (e) 8 g stainless steel 8-type swivel (no additional weight incorporated as with leaded-barrel swivels, which have a lead barrel incorporated into the center); (f) 0.5 m clear 1.8 mm diameter monofilament leader; and (g) terminal tackle, comprising a circle hook crimped onto the leader, with single baited whole mackerel (Table 1a). However, there was some variability of this gear design on individual vessels and between vessels. Seven of the eight inventoried vessels used frozen mackerel (Scombridae, Carangidae, Hexagrammidae, Gempylidae) for bait, ca.

18 cm in length. The eighth vessel used a mix of mackerel, sardine (Clupeidae) and saury (samma, Cololabis adocetus) for bait. All eight vessels used monofilament leaders (half of the vessels had a swivel located 50 cm from the hook with monofilament in between, and half of the vessels did not incorporate a swivel and instead used a ca. 22.5 m length line of monofilament crimped onto the hook). None of the vessels use lightsticks in the gear. All vessels use a mainline shooter to deploy the monofilament mainline from the vessel stern.

Of the eight vessels inventoried for equipment to retrieve protected and vulnerable species (sea turtles, seabirds, sharks), one vessel had a dehooker and one had a dipnet onboard.

In addition to information on species of fish that are always discarded and summary statistics on catch composition, disposition and discard practices (Tables 1b and 1c), one respondent reported sometimes discarding small target catch < 10 kg, and a second respondent reported always discarding opah (moonfish, Lampris regius). Of 7 respondents, six reported that blue sharks are a commonly caught shark species, two identified shortfin mako (Isurus oxyrinchus), sandbar (Carcharhinus plumbeus), copper (bronze whaler, Carcharhinus brachyurus), threshers (Alopius spp.), and silky sharks, and one respondent identified oceanic whitetip sharks as additional commonly caught shark species.

Table 1a
Summary statistics from a survey of Marshall Islands longline tuna vessel operators on fishing gear and methods hypothesized to have a significant effect on catch rates of species groups vulnerable to overexploitation. (N=8 unless noted otherwise).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Mean ± SD of the mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hooks per set</td>
<td>2200.0 ± 57.0</td>
</tr>
<tr>
<td>Hooks between floats</td>
<td>24.3 ± 0.3</td>
</tr>
<tr>
<td>Length of mainline deployed per set (km)</td>
<td>84.5 ± 5.4</td>
</tr>
<tr>
<td>Shallowest hook soak depth (m)</td>
<td>50.4 ± 4.6</td>
</tr>
<tr>
<td>Deepest hook soak depth (m)</td>
<td>303.8 ± 10.2</td>
</tr>
<tr>
<td>Branchline setting speed (s/hook)</td>
<td>8.2 ± 0.1</td>
</tr>
<tr>
<td>Mainline shooter setting speed (m/s)a</td>
<td>5.2 ± 0.1</td>
</tr>
<tr>
<td>Vessel setting speed (km/hr)</td>
<td>15.0 ± 0.6</td>
</tr>
<tr>
<td>Time of day start setting (h:mm)</td>
<td>5:26 ± 0:03</td>
</tr>
<tr>
<td>Time of day end setting (h:mm)</td>
<td>10:30 ± 0:00</td>
</tr>
<tr>
<td>Time of day begin haul (h:mm)</td>
<td>15:30 ± 0:00</td>
</tr>
<tr>
<td>Time of day end haul (h:mm)</td>
<td>1:00 ± 0:00</td>
</tr>
<tr>
<td>Typical depth at fishing grounds (m)</td>
<td>4437.5 ± 62.5</td>
</tr>
<tr>
<td>No. sets per trip made at a submerged feature</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>No. times pass hook through bait</td>
<td>1.0 ± 0.0</td>
</tr>
<tr>
<td>Branchline length (m)</td>
<td>22.6 ± 0.6</td>
</tr>
<tr>
<td>Floatline length (m)</td>
<td>23.8 ± 0.8</td>
</tr>
<tr>
<td>Mainline diameter (mm)</td>
<td>3.8 ± 0.1</td>
</tr>
</tbody>
</table>

a N=7.

Table 1b
Fish species always discarded, survey of Marshall Islands longline tuna vessel operators.

<table>
<thead>
<tr>
<th>Species</th>
<th>% of 8 respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barracuda (Sphyraena barracuda)</td>
<td>75</td>
</tr>
<tr>
<td>Pomfrets (sickle pomfret, Trachichthys steindachneri)</td>
<td>75</td>
</tr>
<tr>
<td>Rays (pelagic ray, Prionoctopus violaceus)</td>
<td>75</td>
</tr>
<tr>
<td>Escolar (Leiognathus flavonotum)</td>
<td>50</td>
</tr>
<tr>
<td>Ophah (moonfish, Lampris regius)</td>
<td>50</td>
</tr>
<tr>
<td>Snake mackerel (Gempylus serpens)</td>
<td>37.5</td>
</tr>
<tr>
<td>Oceanic sunfish (Mole mola)</td>
<td>25</td>
</tr>
<tr>
<td>Rainbow runner (Elagatis bipinnulata)</td>
<td>25</td>
</tr>
<tr>
<td>Yellowtail (yellowtail amberjack, Seriola lalandi)</td>
<td>25</td>
</tr>
<tr>
<td>Black marlin (Makaira indica)</td>
<td>12.5</td>
</tr>
<tr>
<td>Blue marlin (Makaira nigricans)</td>
<td>12.5</td>
</tr>
<tr>
<td>Giant manta ray/pelagic manta ray (Manta birostris)</td>
<td>12.5</td>
</tr>
<tr>
<td>Hammerjaw (Onoosus lowii)</td>
<td>12.5</td>
</tr>
<tr>
<td>Pacific sand lance fish (Ammodictys hexapterus)</td>
<td>12.5</td>
</tr>
<tr>
<td>Wahoo (Acanthocybium solandri)</td>
<td>12.5</td>
</tr>
</tbody>
</table>
Respondents reported that because it is illegal to retain sharks under domestic Marshall Islands law, they do not retain sharks, including shark fins (Table 1c). Of 6 respondents, 4 reported that they catch primarily olive Ridley sea turtles (Lepidochelys olivacea), 1 mostly green sea turtles (Chelonia mydas), and 1 mostly loggerhead sea turtles (Caretta caretta).

Table 2 presents survey summary statistics on factors that affect fuel efficiency, and estimates of fuel consumption rates. Six vessels were constructed of steel, two of fiberglass. All main engines are supercharged and use diesel. One vessel had an ice machine onboard and two had water refrigeration units. The other six vessels obtain ice from a seaport facility. Based on a qualitative evaluation of vessel hull skin condition, one vessel was observed to have a clean hull, four were in fair condition, and one had a large amount of visible marine growth. On average, the engine room of one vessel was undergoing repairs. Based on company records, using data from 2010–2012, Majuro-based vessels consumed a mean of 262,755 l of fuel per year (± 6157 SD of the mean) and landed a mean of 129.8 turtles per trip (± 3.5 SD of the mean) (Derrick Wang, Luen Thai Fishing Venture, personal communication, 19 May 2013).

Information from published and available gray literature on catch rates and levels of vulnerable species in the fishery is summarized in Table 3. Bromhead et al. [68] found that in 2009, the most recent year of available observer data, the fishery had discontinued the use of fishing gear and methods known to be employed to target sharks (using large pieces of fish meat as bait, and placing baited hooks near the surface by attaching branchlines directly to floats instead of to the mainline), which had been employed in previous years of the study period (2005–2008). Bromhead et al. [68] also reported that, in recent years, the fishery had changed methods of making shallow sets at night to making deep sets during the daytime as a strategy to target bigeye tuna.

3.2. First-order estimate of catch Rates, levels and disposition of vulnerable populations and stocks

First-order estimates of catch rates, extrapolated fleet-wide levels, and disposition of vulnerable populations and stocks included in the assessment by taxonomic groups follow.

3.2.1. Sea turtles

Survey respondents reported catching olive Ridley, green and loggerhead sea turtles, and typically catch 3 sea turtles per year. A third of respondents reported that turtles are typically alive upon retrieval (Table 1c). When raised to the 55 vessels in the fishery [66] an estimated 165 turtles are captured per year. Based on survey responses, the estimated sea turtle nominal catch rate is 0.005 turtles per 1000 hooks.

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Table 1c
Summary statistics on catch composition, disposition upon retrieval, and discard practices, survey of Marshall Islands longline tuna vessel operators.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Mean</th>
<th>± SD of the mean</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of caught sharks that are alive upon retrieval</td>
<td>83</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>% of caught sharks for which the carcass is retained</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>% of caught sharks for which fins only are retained</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>No. turtles caught per year</td>
<td>3</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>% of respondents reporting that caught sea turtles are typically alive upon retrieval</td>
<td>33</td>
<td>NA</td>
<td>6</td>
</tr>
<tr>
<td>No. marine mammals caught per year</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>% of caught marine mammals that are alive upon retrieval</td>
<td>80</td>
<td>NA</td>
<td>1</td>
</tr>
<tr>
<td>No. seabirds caught per year</td>
<td>0</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>% of catch with partial shark depredation evidence</td>
<td>1.3</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>No. fish per trip with partial cetacean depredation evidence</td>
<td>2.8</td>
<td>2.1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2
Summary statistics of vessel equipment that effects vessel fuel consumption, survey of Marshall Islands longline tuna vessel operators.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Mean</th>
<th>± SD of the mean</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel registered length (m)</td>
<td>26.2</td>
<td>1.4</td>
<td>7</td>
</tr>
<tr>
<td>Main engine year of manufacture</td>
<td>2005.5</td>
<td>2.3</td>
<td>8</td>
</tr>
<tr>
<td>Main engine size (KW)</td>
<td>389.6</td>
<td>18.5</td>
<td>8</td>
</tr>
<tr>
<td>No. fuel filters main engine</td>
<td>3.3</td>
<td>0.3</td>
<td>6</td>
</tr>
<tr>
<td>No. fuel filters on auxiliary engines</td>
<td>2.6</td>
<td>0.6</td>
<td>7</td>
</tr>
<tr>
<td>Vessel fuel capacity (liter)</td>
<td>31,468.1</td>
<td>2397.8</td>
<td>8</td>
</tr>
<tr>
<td>Generator power (KW)</td>
<td>72.2</td>
<td>8.2</td>
<td>6</td>
</tr>
<tr>
<td>Deck lights power (watt)</td>
<td>500</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>No. deck lights on during setting</td>
<td>2.4</td>
<td>0.2</td>
<td>7</td>
</tr>
<tr>
<td>No. deck lights on during hauling</td>
<td>6.4</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>Distance from seaport to fishing grounds (km)</td>
<td>218.8</td>
<td>13.2</td>
<td>8</td>
</tr>
<tr>
<td>Fuel consumed per trip (liter)</td>
<td>16,349</td>
<td>3,221</td>
<td>8</td>
</tr>
<tr>
<td>Frequency main engine and auxiliary engine oil, oil filters, and air filters are replaced</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>% of respondents that use a fuel additive</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
</tbody>
</table>

---
Table 3
Estimates from previous studies of bycatch levels and rates in Marshall Islands longline tuna fishery.

<table>
<thead>
<tr>
<th>Information on catch rates or levels of vulnerable species</th>
<th>Method for collection of catch data</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on Secretariat of the Pacific Community-held observer program data, from 1995–2009, in 203 observed trips, one seabird (unidentified species) was observed captured by a longline tuna vessel operating within the Marshall Islands EEZ. There was also one record of an albatross landing on a vessel deck, but not interacting with the gear.</td>
<td>Onboard observers</td>
<td>[75]; Peter Williams, personal communication, Secretariat of the Pacific Community, 21 February 2013</td>
</tr>
<tr>
<td>In a total of 1467.26 million set hooks, 1035 marine mammals (unidentified species), 13,399 sea turtles (most not identified to species level, but a high proportion of identified turtles were olive Ridley Lepidochelys olivacea), and zero seabirds were estimated (from an average annual 0.004% onboard observer coverage rate) to be captured in combined tropical deep-set (≥ 10 hooks per basket) pelagic longline fisheries operating in the western and central Pacific Ocean between 15°N and 10°S (which includes the Marshall Islands longline bigeye tuna Thunnus obesus fishery), between 1992 and 2004. About one third of marine mammals were dead and two thirds of turtles were dead upon release.</td>
<td>Onboard observers and logbooks</td>
<td>[76]</td>
</tr>
<tr>
<td>In 2007, through onboard observer coverage of 56 longline trips, observers reported the capture of 4 green (Chelonia mydas), 1 hawksbill (Eretmochelys imbricata), 9 leatherback (Dermochelys coriacea), 5 olive Ridley and 2 unidentified species sea turtles, of which all but 2 of the olive Riddleys were landed dead, and 3 toothed whales (unidentified species) were observed captured, and no interactions with other sea turtle or marine mammal species or seabirds were observed. In 2008, through onboard observer coverage of 42 longline trips, observers reported the capture of 1 green sea turtle, landed dead, and one seabird (unidentified species), and no interactions with other sea turtle species or marine mammals. In 2009, through onboard observer coverage of 26 longline trips, observers reported the capture of 5 leatherback sea turtles, which were all landed dead. There were no observed interactions with other sea turtle species, marine mammals or seabirds in 2009.</td>
<td>Onboard observers</td>
<td>[66,77–79]</td>
</tr>
<tr>
<td>Based on analyses of observer data collected from 2005 to 2009, 22 shark species were observed captured in the Marshall Islands longline tuna fishery, with 80% of the shark catch being comprised of five species: blue (Prionace glauca), silky (Carcharhinus falciformis), bigeye thresher (Alopias superciliosus), pelagic thresher (A. pelagicus) and oceanic whitetip (C. longimanus) shark. Given the low observer coverage rate (ca. 6%) over the study period in the components of the fishery included in the study (Chinese and Federated States of Micronesia-flagged vessels), the authors hypothesized that likely a larger number of rarer shark species are caught in the fishery.</td>
<td>Onboard observers</td>
<td>[68]</td>
</tr>
<tr>
<td>Based on 2009 observer data, sharks and rays composed about 18% of total catch by weight by the Marshall Islands longline fishery. Elasmobranch species composition was: 90% blue shark, 13% silky shark, 10% mako shark (Isurus spp.), 9% oceanic whitetip shark, and 3% other combined sharks and rays.</td>
<td>Onboard observers</td>
<td>[66]</td>
</tr>
</tbody>
</table>
Based on observer data from 2007–2009, there was a mean nominal combined species sea turtle catch rate of 0.006 (± 0.003 SD of the mean) turtles/1000 hooks [77–79]. Of 25 observed captured turtles, 92% were dead upon retrieval [77–79]. Based on rough catch rate estimates by individual sea turtle species, the 55 vessels in the fishery catch 149 leatherback (Dermochelys coriacea), 53 green, 32 olive Ridley, and 11 hawksbill (Eretmochelys imbricata) sea turtles annually, for a total of 244 turtles per year, of which 20 are alive upon capture. This estimate allocated 20 turtle captures of unidentified species to the four species, according to the proportion of the total that each species makes up (e.g., leatherbacks represent 61% of total caught turtles, thus 12 of the 20 unidentified species of turtles were assumed to be leatherbacks).

Extrapolating from an extremely low observer coverage rate, in deep-set longline fisheries operating in the tropical western and central Pacific, an estimated 0.009 sea turtles per 1000 hooks are caught. The predominant species caught was olive Ridleys, and central Pacific of the mean) turtles/1000 hooks [77–79]. Of 25 observed captured turtles, 92% were dead upon retrieval [77–79]. Based on rough catch rate estimates by individual sea turtle species, the 55 vessels in the fishery catch 149 leatherback (Dermochelys coriacea), 53 green, 32 olive Ridley, and 11 hawksbill (Eretmochelys imbricata) sea turtles annually, for a total of 244 turtles per year, of which 20 are alive upon capture. This estimate allocated 20 turtle captures of unidentified species to the four species, according to the proportion of the total that each species makes up (e.g., leatherbacks represent 61% of total caught turtles, thus 12 of the 20 unidentified species of turtles were assumed to be leatherbacks).

Extrapolating from an extremely low observer coverage rate, in deep-set longline fisheries operating in the tropical western and central Pacific, an estimated 0.009 sea turtles per 1000 hooks are caught. The predominant species caught was olive Ridleys, and about a third of turtles were alive upon release [76]. Applying this estimate to the Marshall Islands fishery, 311 turtles are captured annually, of which 104 are alive upon release.

3.2.2. Elasmobranchs

Survey respondents reported catching blue, shortfin mako, sandbar, copper, threshers, silky, and oceanic whitetip sharks, and estimated that 83% of caught sharks are alive upon retrieval (Table 1c). Based on observer data from 2009, the last year the fishery had onboard observer coverage, and the first year that vessels in the fleet discontinued employing gear designed to target sharks [68], an estimated 1438 t of elasmobranchs were caught, which was 18% of the total catch by weight [66]. Elasmobranch catch in 2007 and 2008, when gear used to target sharks was employed, was 26.8% and 35.5% of the total catch, respectively [68,78]. Using the 2009 observer data, predominant elasmobranch species caught in the fishery, by weight, were blue, silky, mako (Isurus spp.), and oceanic whitetip sharks, combined accounting for 62% of the elasmobranch catch [66]. Survey results suggest that a large proportion (83%) of sharks are released alive, and the remainder are discarded dead.

3.2.3. Marine mammals

Seven survey respondents reported never catching a marine mammal. One respondent reported having captured a marine mammal, but did not provide an estimate of the typical number caught per year (Table 1c). Respondents reported evidence of cetacean depredation of about 3 fish per trip (0.1 depredated catch per 1000 hooks) suggesting that it is probable that on rare occasions cetacean capture events likely do occur. One respondent estimated that 80% of marine mammals are alive upon retrieval.

Based on observer data from 2007–2009, there was a mean nominal cetacean catch rate of 0.0006 (± 0.0006 SD of the mean) cetaceans/1000 hooks. No information was reported on species captured or disposition [77–79]. Extrapolating fleet-wide, the fishery catches 21 cetaceans annually.

In deep-set longline fisheries operating in the tropical western and central Pacific, an estimated 0.001 marine mammals are caught per 1000 hooks, and about two thirds were alive upon release [76]. No information was reported on predominant species captured. Applied to the Marshall Islands fishery, 35 marine mammals are captured annually, of which 23 are alive upon release.

3.2.4. Seabirds

Survey respondents reported that they do not catch seabirds. Based on available observer data covering the period from 1992 to 2009, in 203 observed trips in the fishery, there is only one record of a seabird capture event of an unidentified species, and one observation of an albatross alighting on a vessel deck [75–79]; (Peter Williams, personal communication, Secretariat of the Pacific Community, 21 February 2013). These data produce a nominal catch rate point estimate of 0.0002 seabirds/1000 hooks with extremely high uncertainty given only a single observed catch event. Raised fleet-wide, a very rough, conservative estimate is that the 55 vessels catch 6 seabirds per year.

3.3. Conservation threat from fishing mortality of vulnerable species

Six of the seven marine turtle species are categorized as Vulnerable, Endangered, or Critically Endangered globally by the IUCN Red List of Threatened Species, including the five species identified as having been observed captured in this fishery: green (Endangered), hawksbill (Critically Endangered), leatherback (Critically Endangered), loggerhead (Endangered), and olive Ridley (Vulnerable) [80]. The IUCN Marine Turtle Specialist Group is in the process of updating sea turtle Red List assessments, which will include new assessments for each subpopulation in addition to IUCN-required global species-level assessments (Bryan Wallace, personal communication, Red List Focal Point, IUCN Marine Turtle Specialist Group, 13 April 2013). This will provide the relevant level of information on risk of extinction needed to support assessment population viability risks from fishing mortality [69].

The fishery overlaps with four RMUs: the green sea turtle West Pacific/Southeast Asia RMU (categorized as low risk), hawksbill sea turtle west central Pacific RMU (low risk), leatherback sea turtle west Pacific RMU (high risk), and olive Ridley sea turtle west Pacific RMU (low risk) [69].

Of elasmobranch species documented captured in the fishery, IUCN lists two shark species (scalloped hammerhead Sphyrna lewini and great hammerhead Sphyrna mokarran) as globally Endangered, and seven shark species as globally Vulnerable (bigeye thresher Alopias superciliosus, pelagic thresher Alopias pelagicus, oceanic whitetip C. longimanus, shortfin mako, longfin mako I. paucus, common thresher Alopias vulpinus and sandbar shark) [80]. The north Pacific blue shark stock’s biomass is close to its MSY-based reference point and the exploitation fishing mortality rate is approaching the MSY-based reference point, based on data through 2002 [70]. More recent observations of declining trends in standardized catch rates (relative, local abundance) and increased targeting of blue sharks by some fisheries suggest further declines in absolute abundance have occurred since 2002 [45,49,81]. Both stocks of western and central Pacific Ocean oceanic whitetip and silky sharks are overfished and overfishing is occurring [71,72].

Based on indicators of temporal trends in relative and absolute stock abundance, the Western and Central Pacific Fisheries Commission (WCPFC), the tuna regional fisheries management organization with a convention area that includes the Marshall Islands, adopted a shark conservation and management measure that identifies 13 ‘key shark species’, stocks that were determined to be of highest priority for research, conservation and management, most of which were observed captured in the Marshall Islands fishery, including all five of the predominantly caught shark species [82–85]. This designation was based on ad hoc considerations of several factors, including: (i) high susceptibility to fishing mortality based on the results of an ecological risk assessment; (ii) ease of identification; and (iii) frequency of reporting in annual catch data [82].

Of 16 cetacean species that are thought to occur in the Marshall Islands EEZ, the sperm whale (Physeter macrocephalus) is the one odontocete (suborder Odontoceti, toothed whales) categorized as globally Vulnerable by IUCN, however, several odontocetes are categorized as Data Deficient [80,86]. Baleen whales are less likely to interact with longline gear relative to toothed whales [87,88]. There is little knowledge of the population structure and
Table 4: Information considered in an assessment of the relative ecological risk to species and populations across taxa, Marshall Islands longline tuna fishery.

<table>
<thead>
<tr>
<th>Species</th>
<th>Population/stock/RMU</th>
<th>Criterion and Aim of Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fishery Removal Level</td>
</tr>
<tr>
<td>Leatherback sea turtle</td>
<td>West Pacific RMU</td>
<td>140</td>
</tr>
<tr>
<td>Hawksbill sea turtle</td>
<td>West central Pacific RMU</td>
<td>11</td>
</tr>
<tr>
<td>Green sea turtle</td>
<td>West Pacific/Southeast Asia RMU</td>
<td>38</td>
</tr>
<tr>
<td>Olive Ridley sea turtle</td>
<td>West Pacific RMU</td>
<td>22</td>
</tr>
<tr>
<td>Blue shark</td>
<td>North Pacific Ocean stock</td>
<td>19</td>
</tr>
<tr>
<td>Silky shark</td>
<td>Western and central Pacific Ocean stock</td>
<td>19</td>
</tr>
<tr>
<td>Oceanic whitetip shark</td>
<td>Western and central Pacific Ocean stock</td>
<td>22</td>
</tr>
</tbody>
</table>

a. Sea turtle Regional Management Unit (RMU) and risk categorizations [60,91].
b. Number per year. Conservatively assumes 100% post-release mortality of the 8% of caught turtles that are released alive, in part due to the limited possession of sea turtle handling and release equipment by the inventoried vessels. Information on age class and sex of removals was not available.
c. Tonnes per year. Based on 2009 observer data records, the last year the fishery had onboard observer coverage, and the first year that vessels in the fleet discontinued employing gear designed to target shark catches [66].
Based on the rough estimate that 21% of caught sharks die from the interaction, where an estimated 17% of caught sharks are dead upon retrieval [79], and based on limited published estimates of shark post-release survival, 4% of caught sharks die after release (83% of sharks are released alive, of which 5% later die due to injuries and stress resulting from the fishery interaction) [4,92–95]. Information on age class and sex of removals was not available.
d. Red List of threatened species categorizations [80].
e. Estimates of first, minimum threshold population size (absolute abundance), density (relative or local abundance), or other indices of threshold abundance and density, for these stocks were unavailable to compare with estimates of current stock biomass levels.

f. Faith et al. [96], employing method described in Faith et al. [74]. PD50 scale ranges from a low of 0.5 to a high of 2.0 [73–74].
g. Sea turtles do not occupy upper trophic levels and are not a part of an apex predator guild of coastal or pelagic ecosystems.

h. The understanding of whether a pelagic ecosystem keystone predator or guild exists, the relative importance of species and age classes to the functioning of the pelagic ecosystem apex predator guild, and functional links between pelagic ecosystem food webs (trophic levels), is not well understood [53,95,99]. Models of the North Pacific Subtropical Gyre to investigate whether the ecosystem contains keystone species concluded that there was no single guild of species that functions as a keystone [53,96,98,99]. There may not be a pelagic ecosystem keystone species because of a high functional redundancy within upper trophic levels [99].

i. As these species are currently a small proportion of total biomass of pelagic and coastal ecosystems, they are unlikely to serve as pelagic or coastal ecosystem foundation species [100]. However, historically, some sea turtle species, and other mega-vertebrates, were substantial components of biomass of some marine communities (e.g., green sea turtles and Caribbean sea grass ecosystems [101,102]).
conservation status of populations of cetacean species that overlap with the Marshall Islands EEZ [86]. Of 35 species of seabirds with distributions that overlap the Marshall Islands EEZ, three are categorized as globally Vulnerable (black-footed albatross Phoebastria nigripes, Stejneger’s petrel Pterodroma longirostris, Buller’s shearwater Puffinus bulleri) and three as Near Threatened (Laysan albatross Phoebastria immutabilis, mottled petrel Pterodroma inexpectata, sooty shearwater Puffinus nativitatis) by IUCN [80,89]. However, the relative abundance in the tropical western and central Pacific Ocean of elasmobranch and large petrel species, and other seabird species known to be susceptible to capture in pelagic longline fisheries, is extremely low [90].

3.4. Relative risk between taxonomic groups

Using three criteria to assess relative risk within and between taxa, Table 4 summarizes available information for species of sea turtles and elasmobranchs included in this ERA. Information on age classes and sex ratios taken in the fishery was unavailable. The lack of information on population risk of extirpation for the shark species precludes an assessment of relative risk at this taxonomic level. Based on species-level global conservation status and estimated annual levels of fishing mortality, the following rank-order is supported: leatherback sea turtle, hawksbill sea turtle, green sea turtle, olive Ridley sea turtle, oceanic whitetip shark, blue shark, and silky shark. The ranking of the oceanic white tip stock above as higher risk relative to the other two shark stocks is based largely on the IUCN global species categorizations. The blue shark stock was ranked as higher risk relative to the silky shark stock due to the blue shark having a higher catch level and higher phylogenetic uniqueness. PD50 species scores indicated that the blue shark is relatively more phylogenetically unique than the other two shark species. PD50 scores were not available for the sea turtle species for comparison to the shark species, however, the relevance of a comparison of these unrelated groups is questionable [103]. A comparison of importance in regulating ecosystem processes and structure was inconclusive, due to there likely being no pelagic ecosystem keystone species guild, and limited understanding of the historical role of sea turtles as foundation species in coastal ecosystems (Table 4, footnotes 8 and 9).

4. Discussion and conclusions

The mixed-level ERA for this data-deficient fishery enabled a first-order estimate of catch levels and rates of vulnerable populations, and identification of the relative degree of conservation risk posed by removals. Factors were also identified that are compromising optimal fuel efficiency. Findings identify opportunities to introduce changes to fishing methods and gear and vessel equipment to implement a precautionary approach to mitigate risks to population viability and reduce greenhouse gas emissions.

4.1. Level 1 and 2 ERA information sources

Alternative information sources for Level 1 and 2 fishery ERAs, including: surveys; onboard and dockside human observers; electronic onboard monitoring; logbooks; and electronic vessel monitoring systems, each have positive and negative aspects. Fisher surveys and vessel inventories provide a critically important first-order qualitative understanding of relative and absolute risks where previously little or no information was available [110]. There is generally low certainty of findings that rely only on information obtained from social surveys [104]. Accurate, current information on gear designs and fishing practices may only be obtainable via dockside inventories and surveys in this and other fisheries where monitoring, including onboard observation rates and data collection protocols, is limited and research grade observer data are not publicly available [2].

Level 2 ERAs have assessed low-productivity species’ susceptibility to fisheries overexploitation by determining whether a population’s distribution overlaps spatially and temporally with fishing grounds [3,6,10,105,106]. Instead, in this study, susceptibility of low-productivity species of being captured was estimated in part through analysis of capture records from observer data. This latter method is more likely to avoid false positives. For instance, despite there being numerous seabird species that are in groups documented to be susceptible to capture in pelagic longline fisheries, including albatrosses, petrels and shearwaters [107,108], that have distributions that overlap with the Marshall Islands fishery [89], nominal seabird interactions have been observed in this and other tropical western and central Pacific pelagic longline fisheries, most likely due to the low relative abundance of these species in this region [75,90].

4.2. Catch rates, levels and disposition

This mixed Level 1 and 2 ERA provided first order estimates of catch levels and rates for this data-deficient fishery. There is low certainty in the estimated catch levels and rates due to extremely low observer coverage rates and small sample sizes; the most recent year of available observer records being prior to documented changes in gear (e.g., discontinued use of wire leaders, change to the depth of gear) and methods (e.g., time of day of fishing operations) that likely have had large and significant effects on catch rates; the discontinued use in 2009 of shark-targeting shallow-set branchlines and change in the time of day of setting and depth of baited hooks; and inherent limitations in relying on data from social surveys [49,67,68,104]. The vessel inventory documented that the fishery no longer employs wire leaders, is gradually replacing tuna hooks with wider circle hooks, and may have made other changes to gear and methods since the end of the observer database time series that are documented in studies of other fisheries to result in significant effects on catch rates [32,49].

The fisher survey, observer data from the fishery from 2007–2009 [77–79], and observer data from regional deep-set longline fisheries from 1992–2004 [76] provided consistent, same order of magnitude, estimates of turtle interactions. The lack of consistency in survey respondents’ identification of predominant species of sea turtle caught might be due to poor identification skills. Using the last three years of observer program data as the best estimate, the Marshall Islands fishery is estimated to have a sea turtle catch rate of 0.006 turtles/1000 hooks, with a fleet-wide annual total catch of 244 turtles, of which 92% were dead upon retrieval. The total turtle catch was comprised of 61% leatherback, 22% green, 13% olive Ridley, and 4% hawksbill sea turtles. The three available sources estimating the disposition of sea turtles upon retrieval consistently reported that most are dead, which is expected for deep-set fisheries [109]. Current sea turtle catches may be lower than this estimate due to recent increased proportion of wider circle hooks and deeper setting [32].

After discontinuing the use of gear to target sharks [68], observer data for 2009 document elasmobranch catches were 18% of the total catch, down from an average of 31% in the previous two years [66]. Current shark catches have likely been further reduced due to the recent change from using wire to monofilament leaders and deeper setting, offsetting a possible small increase in elasmobranch catch from a gradual replacement of J-shaped tuna hooks with circle hooks [32,49,67,110]. Relative to other deep-set longline tuna fisheries, a high proportion of the total catch is elasmobranchs [45]. Predominant elasmobranch species caught in the fishery are blue, silky, mako, and oceanic whitetip sharks [66]. Survey respondents report that there is now no shark retention, and that about 83% of caught sharks are alive when retrieved.

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The two information sources used to estimate cetacean catch rates [76–79] resulted in consistent, same order of magnitude, estimates. The cetacean catch rate best estimate from the most recent available three years of observer data from the fishery is about 0.0006/1000 hooks, resulting in an estimated fleet-wide annual catch of 21 cetaceans. Observer records indicate that most (66–80%) cetaceans have been alive upon retrieval. No information was found on predominant cetacean species that interact with the fishery. A recent change to gradually replace tuna hooks with wider circle hooks may have reduced cetacean catches [32].

Available information suggests that seabird bycatch levels and rates in the fishery are extremely low. Based on a single recorded seabird capture event, the fishery might catch six seabirds annually.

4.3. Post-release survival

Unlike elasmobranchs and cetaceans, given that most turtles are dead upon retrieval, there is a smaller capacity for sea turtle conservation from improved sea turtle handling and release practices relative to the capacity from improved methods to avoid and minimize catch rates. However, given the extremely poor conservation status of some sea turtle populations and that the fishery overlaps with two high-risk RMUs, and the rough estimate that ca. 20 turtles are annually released alive, efforts to optimize post-release survival might be worthwhile. Of the eight inventoried vessels, six lacked any equipment for safe handling and release of sea turtles, and two had partial equipment required to be onboard under the relevant binding measure adopted by the WCPFC [111]. Under this measure, longline vessels are required to carry and operators are required to use line cutters, de-hookers and dipnets to handle and release caught and entangled sea turtles [111].

The observation by Bromhead et al. [68] that in 2009 the fishery had discontinued the use of gear and methods to target sharks is consistent with the current study observations of no wire leaders, no squid bait, and the shallowest hook is set at about 50 m depth. No information was available on elasmobranch handling and release practices by crew in this fishery, which can have a large bearing on post-release survival [4,112,113]. A Western and Central Pacific Commission measure on sharks prescribes, “...the release of live sharks that are caught incidentally and are not used for food or other purposes,” but does not describe elasmobranch best practice handling and release practices [83]. General knowledge of elasmobranch post-release survival rates is limited [4,112,113].

No information was available on cetacean handling and release practices by crew in this fishery, which can have a large bearing on post-release survival [87]. No measures prescribing or recommending marine mammal handling and release practices by pelagic longline vessels have been adopted by WCPFC [2]. Results of methods for estimating the probability of post-release mortality of cetaceans caught in pelagic longline gear suggest that about 75% of those released alive could die later due to injury sustained during the fishery interaction [88].

Information on the disposition or crew handling and release practices of the one seabird observed caught in the fishery was not available, which can affect the probability of post-release survival [105]. A WCPCF seabird measure does not describe best practice seabird handling and release practices [114].

Species-specific differences in disposition and post-release survival [4] should be considered if these estimates are used in models for assessing population-level effects.

4.4. Relative risk within taxonomic groups

Of sea turtle species, the leatherback sea turtle is estimated to have the highest relative conservation risk from mortality and injury in this fishery, followed by the hawksbill sea turtle. This ranking is based on leatherbacks making up a higher proportion (61%) of total turtle captures than hawksbills (4%). The fishery overlaps with ‘high risk’ RMUs for both species. The next highest relative risk within this group is for green sea turtles, followed by olive Ridley’s. Greens were a larger proportion (22%) of the total turtle catch than olive Rydies (13%). The fishery overlaps ‘low risk’ RMUs for both species. Loggerhead sea turtles are the lowest relative risk of affected sea turtle species based on the fishery not overlapping Pacific loggerhead RMUs, and because this species’ distribution may not overlap with the fishery.

Sea turtle RMUs and risk categorizations, defined by Wallace et al. [69,91], were selected as the optimal method for assessing relative risks within this taxonomic group. Sea turtle RMUs encompass multiple nesting sites, nesting populations and breeding populations, and as such, are units deemed optimal for assessing the conservation status of marine turtles and for management applications [69]. Given the method for defining RMU boundaries, they are intended to define core habitats and life stages, and areas of a species’ global distribution that falls outside of RMUs are by definition lower conservation priority. Wallace et al. [91] determined relative risk scores for each sea turtle RMU on an assessment against five criteria: population size, recent trend, long-term trend, rookery vulnerability, and genetic diversity. As such, the high risk RMUs correspond to small, decreasing, low diversity RMUs.

Based on a low observer coverage rate, 22 shark, skate and ray species have been recorded as captured in the fishery. Given larger sampling effort, it is likely that a larger number of rarer elasmobranch species would be observed caught [66,68,77–79]. Information on conservation status is available for a small proportion of elasmobranch stocks. IUCN Red List global species-level categorizations are not necessarily indicative of the status of populations that overlap with the fishery. Of elasmobranch species documented to be captured in the fishery, stock assessments are available for blue, oceanic whitetip and silky sharks. Of these three assessed stocks, relative to the north Pacific blue shark stock, there may be a higher conservation risk from fishing mortality in this fishery for the oceanic whitetip and silky shark stocks, which are both overfished and overfishing is occurring [71,72], and which were 9% and 13% of total elasmobranch catch, respectively [66]. The north Pacific blue shark stock may be near or possibly below B_{MSY} [70,81]. Despite a higher proportion of the catch being comprised of blue sharks relative to oceanic whitetip and silky sharks, the blue shark stock is likely in better condition.

There are no species-level records of cetacean interactions in the Marshall Islands or regional deep-set pelagic longline tuna fisheries [76–79]. Furthermore, there is limited knowledge of both the population structure and conservation status of populations of cetaceans that overlap with the Marshall Islands EEZ [86]. This dearth of information precludes assessing the relative or absolute risk to cetacean populations subject to fishing mortality and injury in the fishery.

Data quality is also insufficient to estimate relative risks to seabird populations captured in the fishery. The fishery is understood to have nominal overlap with the distributions of seabird species known to be susceptible to capture in pelagic longline fisheries [75,76,90].

4.5. Relative risk between taxonomic groups

One management implication was apparent from the findings of the between-taxa relative risk assessment. Of the fishing gear and methods assessed in this ERA, hook design is the one factor that presents a potential inter-taxa conflict, where use of circle hooks in place of J-shaped hooks causes large reductions in sea turtle catch rates but in some fisheries can cause small but significant increases in elasmobranch catch rates, discussed in
Section 4.8.1. Numerous other factors may also pose conflicts between vulnerable bycatch taxa include, including, for instance, the time of day of setting, season, spatial location, and gear depth when soaking [49,115,116], which could be explicitly assessed in a Level 3 ERA.

There is no unequivocal method to compare fishery risks between taxonomic groups, e.g., are population-level risks to sea turtle populations and RMUs higher or lower than risks to shark populations [30]. Three criteria were used here as the basis for estimating relative risks within and between taxonomic groups: category of global and population or RMU conservation status, phylogenetic distinctiveness, and importance of role in regulating ecosystem integrity. The results of applying each criterion independently would most likely result in different rankings of relative risk, but the three criteria can be considered collectively and are not mutually exclusive approaches to assessing relative risk.

The aim of assessing the criterion on population- and species-level conservation status is to determine the absolute risk that the fishery will cause population extinctions or species extinctions to meet an objective of avoiding and minimizing the risk of permanent loss of populations and species, and to compare relative risks to populations and stocks to meet an objective of guiding priority-setting for research and management, e.g., which stock is a highest priority for conducting an updated or new stock assessment. Application of the criterion would provide a high risk ranking to endemic, restricted-range taxa with small populations [46,117].

The aim of assessing the criterion on relative phylogenetic uniqueness is to avoid having the fishery cause the loss of genetic diversity as a result of the extinction of an entire higher taxonomic group and evolutionary lineage. Ranking relative risk of species affected by a fishery based on taxonomic distinctiveness enables reducing the risk of losing species lacking or with few close taxonomic relatives with relatively distinct genetic diversity that are of relative importance for the potential continuation of evolutionary processes [73,74,118–120]. However, evolutionary histories are not available for all taxonomic groups, and there is no agreed standardized way to compare the relative taxonomic distinctness of species from unrelated groups [103].

The aim of assessing the criterion on relative role in regulating ecosystem structure and processes is to prevent the fishery from removing populations that are critical to maintain broad community- and ecosystem-level integrity [30]. Keystone species have relatively large roles in regulating an ecosystem’s functioning and structure that is disproportionate to their abundance and/or biomass (i.e., they tend not to be the dominant components of a community or ecosystem), and tend to be of higher trophic levels [121]. Foundation species have a relatively large role in regulating ecosystem functioning and structure, various other species depend on foundation species’ health such that their extinction can cause extinction cascades, they tend to be of lower trophic levels, and are common at the spatial scale being considered [122]. Unlike keystone species, foundation species tend to be numerically dominant components of their ecosystem, and it is this dominance that results in their importance in effecting ecosystem structure and functioning. However, large gaps in knowledge of many coastal and marine ecosystems as well as functional links between ecosystems may prevent application of this approach.

4.6. Absolute risk of population extirpation of market species of fecund marine fishes

Populations and RMUs were selected for inclusion in this ERA that have a high risk of extirpation due to their high susceptibility to capture in pelagic longline fishing gear, susceptibility to other anthropogenic sources of mortality, and their K-selected life-history characteristics, including low productivity. Populations and stocks of market and non-market species with r-selected life history characteristics, however, were excluded, that may be at risk of extirpation or at risk of protracted or permanent alteration to their roles in regulating Pacific Ocean pelagic ecosystems, in part due to removals from the Marshall Islands fishery. Information on both threshold minimum viable population sizes and fishing mortality rates beyond which populations are at risk of extirpation [11,43,123–127], thresholds beyond which roles in ecosystem regulation are compromised, and recent average and current fishing mortality rates and biomass are not available for some stocks of fecund market and non-market species of fish that are subject to mortality in the Marshall Islands fishery. Furthermore, this ERA did not consider identifying other species that might have low resistance to fishing mortality, such as endemics with restricted ranges, species with sporadic recruitment, and ecological specialists [11,30,44]. Biological reference points where increased fishing effort and mortality risks irreparably damaging a fish stock (Fcrash, the fishing mortality rate that will drive a population to 1/1000 of virgin biomass, or Bcrit, the minimum viable population size below which population extirpation is imminent) have not been identified for any tuna and tuna-like species (socombids and billfishes) that have also been considered or used in the management of these fisheries. When Bcrit, minimum viable density, or similar threshold is exceeded, a stock may experience niche replacement, reduced genetic diversity, reduced viability in reproducing, etc. [62,128–134].

There is uncertainty in available information on the relative and absolute extinction risk in marine fishes due to disagreement over the application of threat-listing methods to fecund market species of marine fish. Threat-listing programs, including those implemented by IUCN and the Convention on International Trade in Endangered Species of Wild Flora and Fauna, have recently been applied to marine species. For example, the use of a decline rate criterion by these and other listing schemes has been criticized by some as over-estimating extinction risk for many fecund market species of marine fish, and in general, there is lack of consensus that population rate of decline is a valid predictor of relative or absolute risk of extinction risk [11,127,135].

Dulvy et al. [11] discusses how the disparity between effective and census population sizes, the effect of reduced population size on population growth rate, and effect on recruitment if there are interconnected subpopulations would contribute to defining Bcrit for highly fecund broadcast spawning marine fish. For tuna and tuna-like species, however, there is no relationship between recruits and the abundance, biomass and egg production by adults classes, where only at extremely low population sizes is egg production likely to be a limiting factor for recruitment [99,136]. As a result, populations/stocks of tuna and tuna-like species may have a relatively low risk of extirpation.

When current biomass falls below Bmsy for a sufficiently long period, this could trigger a decrease in supply, increase in both value and global demand, and concomitant increased incentive to increase fishing effort [137]. Thus, market forces may drive the biomass of an overexploited stock to a critical level if the governance system is ineffective. Stock-specific and multispecies limit reference points can be effectively employed as management and economic thresholds that when exceeded trigger pre-agreed controls designed to avoid and rebuild overfished stocks and avoid a spiral towards Bcrit, but per se are not suitable for use in ERAs as an ecological critical threshold.

4.7. ERA threshold for unacceptable impact and EBFM ecological objectives

There are variable definitions of what constitutes limits of acceptable fisheries impacts. International mechanisms generally
recommend or require minimizing, reducing or eliminating ‘bycatch’ and minimizing fisheries impacts on non-target species, and preventing fisheries from causing significant adverse impacts on threatened and endangered species [33,36,138–141]. They do not explicitly consider mitigating risk of fisheries causing irreparable damage to populations and stocks. In addressing habitat impacts, several regional fisheries management organizations have adopted binding measures that include explicit definitions for identifying benthic areas as Vulnerable Marine Ecosystems (e.g., seamounts, hydrothermal vents, cold water corals and sponge fields), based on threshold catch rates of live corals and sponges, areas which may be immediately subject to a move-on provision, and later be considered for permanent closure to demersal fisheries [142–145]. International guidance for managing shark fishing mortality, which can be a target, incidental retained bycatch, or discard bycatch species [45], calls for achieving long-term sustainable exploitation [34]. MSC, a global organization that defines an ecological sustainability standard for the certification of wild capture fisheries, includes as one of a suite of criteria a criterion with an objective to avoid and minimize injury and mortality of ecological sustainability standard for the certiﬁcation of wild capture fisheries, includes as one of a suite of criteria a criterion with an objective to avoid and minimize injury and mortality of endangered, threatened and protected species and stocks [7]. MSC defines “unacceptable impacts” as those that preclude meeting national or international requirements for protection and rebuilding, and hinder recovery and rebuilding [8]. Some domestic fishery management authorities have established quotas to limit the fishing mortality or catch levels of vulnerable populations, where limits are based upon models that estimate ﬁshing mortality levels that would adversely affect population viability (e.g., leatherback and loggerhead sea turtle bycatch caps in the Hawaii longline swordfish ﬁshery [26,27]). Potential biological removal under the U.S. Marine Mammal Protection Act is the maximum allowable annual removal limit for a stock of marine mammals, estimated as the number of individuals that can be removed through anthropogenic mortality sources without reducing the stock below its optimum sustainable population level [20]. As reviewed in the Introduction, there have been a range of other Level 3 ERA methods to assess population-level effects from ﬁshing mortality, where data limitations often preclude rigorous estimates of an individual ﬁshery’s risk of causing population declines and exceeding a threshold risk of extinction.

Thresholds for acceptable levels of ﬁshery ecological absolute risks can be described as ecological objectives of ecosystem-based ﬁsheries management to: (i) Stay within ecosystem-level multispecies limit reference points, where declines in market, associated and dependent species and guilds, while not necessarily risking population extinctions, can alter ecosystem structure, processes, resistance and resilience, in addition to having adverse socioeconomic consequences (e.g., not sustainably producing maximum multispecies yields of market species); (ii) Manage ﬁsheries to prevent population extirpations and species extinctions, including of phylogenetically unique species, of associated and dependent species relatively vulnerable to ﬁsheries exploitation due to their life history characteristics and susceptibility to mortality in ﬁsheries, as well as of fecund, widespread species, thus avoiding biodiversity loss at genetic- to species-levels; (iii) Manage ﬁsheries to allow rebuilding and recovery of endangered, threatened, and overexploited units; (iv) Manage ﬁsheries to prevent exceeding stock-speciﬁc biological limit reference points that produces maximum sustainable yields for stocks of market species (more a socioeconomic than ecological objective, however exceeding MSY-based limit reference points can trigger conditions that lead to exceeding thresholds that lead to population extirpations, Section 4.6); (v) Mitigate habitat degradation and loss from ﬁshing operations, including disturbance of sensitive ecosystems and sites of relatively high biodiversity value; and (vi) Minimize collateral, indirect ecological effects of ﬁshing, such as reducing genetic diversity, altering evolutionary characteristics of populations, and altering community and food web structure and processes so as to avoid exceeding ecosystem regime shift tipping points, where protracted or irreversible changes to ecosystem structure and processes occur [2,4,11,29,30,43,46]. Whilst the lack of an agreed deﬁnition of unacceptable ecological risk from ﬁshing is unlikely to be resolved, agreement for standardized application of ERAs to determine relative risk, e.g., in terms of estimated effects on population viability or sites of high biodiversity value, is likely achievable.

4.8. Fishing gear and methods

4.8.1. Hook type

The ﬁshery predominantly uses a mix of 14/0 and 15/0 circle hooks, with a small proportion of narrower J-shaped tuna hooks. There is no empirical information available on temporal changes in hook type use in the ﬁsh, but qualitative evidence (all replacement hooks are 14/0 and 15/0 circle hooks) suggests that vessels have been gradually replacing tuna hooks with wider circle hooks. There is no information available on the effect of hook design and width on catch rates of vulnerable species in the Marshall Islands ﬁshery. There is, however, a large body of evidence that use of wider circle hooks in place of narrower J and tuna hooks reduces sea turtle catch rates and injury primarily in shallow-set but also in deeper-settling pelagic longline ﬁsheries [32]. Wider hooks are understood to reduce captures of hard shelled turtles, which tend to get caught by biting a baited hook. Leatherback turtles tend to get caught by becoming fouled-hooked in the body and entangled; circle hooks may reduce leatherback capture due to their shape [32,35]. For turtles that ingest a hook, circle hooks result in a lower proportion of turtles deeply swallowing the hook relative to J-shaped hooks, hypothesized to result in reduced degree of injury [4,105,146].

Studies in different pelagic longline ﬁsheries have documented variable effects of the single factor hook shape (circle- vs. J-shaped tuna and J hooks) on elasmobranch catch rates [32,45,49,110]. Several studies have documented no signiﬁcant effect [147–155], signiﬁcantly higher [146,152,153,155–160], and signiﬁcantly lower [147,154,161,162] catch rates of some elasmobranch species on circle hooks relative to catch rates on J or tuna hooks. Several of these studies, however, did not employ methods that enabled a determination of the effect of the single factor of hook shape on catch rates, where experiments included treatments with differences in multiple factors (e.g., hook shape and width), and analyses of observer program data did not explicitly account for potentially signiﬁcant explanatory factors through the development of standardized catch rate models [49]. This likely explains the high variability in reported ﬁndings on the effect of hook shape on elasmobranch catch rates. A recent meta-analysis that aimed to determine the effect of hook shape on shark catch rates from data pooled from multiple studies unfortunately did not screen studies to include only those with ﬁndings on the effect of the single factor hook shape on elasmobranch catch rates [110]. Some studies have demonstrated that the factor hook shape has a smaller effect on elasmobranch standardized catch rates relative to other factors, including bait type, leader material, depth of terminal tackle, time and spatial location of ﬁshing effort, and hook factors other than shape (e.g., width at narrowest position, degree of offset, orientation of point) [49,163]. In some studies, a signiﬁcantly higher proportion of sharks were alive upon retrieval when caught on circle hooks relative to captures on J and tuna hooks [160,164], however, a larger number of studies found no signiﬁcant effect of hook shape on at-vessel disposition of elasmobranchs [147,148,154,155]. Thus, while there might be a small but signiﬁcantly higher shark catch rate on circle hooks relative to similar-width J-shaped hooks in some ﬁsheries, there may be a higher probability of survival for those caught on circle hooks if the sharks are released alive, and there may also be a higher probability
of survival of sharks that become hooked but escape before gear retrieval when circle hooks are used instead of J-shaped hooks.

The benefit to sea turtles of using circle hooks might outweigh the cost to affected elasmobranch populations in the Marshall Islands fishery. At the species level, sea turtles have a higher vulnerability of extinction relative to shark species, based on IUCN Red List categorizations [80]. Furthermore, the fishery employs other gear designs that result in reduced elasmobranch catch rates (no wire leader, fish instead of squid for bait), factors that likely are larger effects on shark catch rates relative to hook shape. [45,49].

4.8.2. Bait and baiting
The fishery uses predominantly whole mackerel for bait, which is single-baited onto hooks. The use of whole fish instead of squid for bait has been found to significantly reduce both sea turtle and elasmobranch catch rates in pelagic longline fisheries [32]. Using fish instead of squid for bait is understood to cause a significant, ca. 35%, decrease in shark CPUE [32]. The effect of the independent factor of bait type on sea turtle catch rates is not well understood, as most studies have compared sea turtle catch in treatments with differences in multiple factors (usually hook width, hook shape, and bait type) [109]. Single hooking fish bait instead of multiple hook threading may reduce hard-shelled sea turtle catch rates [109,146].

4.8.3. Leader material
As of 2009, the fishery was documented to be using wire leaders [68]. The inventory found that all vessels had monofilament leaders, suggesting that sometime between 2009 and 2012 the vessels in the fishery eliminated the use of wire leaders. Significantly lower shark catch rates occur with monofilament leaders vs. leaders of more durable material (wire, multifilament nylon) because sharks can bite through the monofilament [32,67]. However, the degree of injury and post-escapee mortality after biting through a leader with a hook and trailing monofilament attached is not known [4].

4.8.4. Hook and branchline diameter
Longline gear employing ‘weak’ hooks are designed so that when large-mass cetaceans are hooked, they can straighten the hook and escape, but large target fish cannot exert enough pull strength to straighten the hook [87,165–167]. To be effective, the hook must be the weakest component of the branchline and terminal tackle, so that the hook straightens before any of the other components of the branchline fail. Otherwise, the cetacean would escape with terminal tackle attached, which may result in an increased probability of post-release mortality. For example, to reduce the capture and probability of mortality of false killer whales (Pseudorca crassidens), the Hawaii longline tuna fishery is required to use circle hooks with a wire diameter of ≥ 4.5 mm with ≤ 10 degree offset, and branchline and leader breaking strength must be ≥ 181.4 kg (400lb), and the monofilament nylon line must have ≥ 2.0 mm diameter [27,168]. For the Marshall Islands fishery, information is needed to determine (i) if there are problematic cetacean interactions; (ii) what kg of pull is required to straighten the hooks and break the branchlines with components currently in use; (iii) do the hooks bend or break in a manner that enables cetacean escape; and (iv) what kg of pull cetaceans determined to be at risk from interactions with the fishery, if any, can exert.

4.8.5. Depth of terminal tackle
The survey respondents estimated that baited hooks soak between 50–300 m. The inventory findings of a mainline shooter (used to deploy the mainline slack, optimizing sinking), 24 hooks per basket (between floats), 24 m length floatlines, and 23 m length branchlines were consistent with the survey respondents’ estimates. The limited use of weights in branchlines reduces the depth of baited hooks during the soak. Catch rates of sea turtles and sharks could be reduced through deeper setting, optimally with all hooks soaking below 100 m [35,45,109,169,170]. However, even with terminal tackle below 100 m, overlap with the diel vertical distributions of some elasmobranchs would continue, depending on the timing of the gear soak [49,171].

4.8.6. Soak time and time of day of fishing operations
Longer duration of soak time (total time baited hooks are in the water) has been found to significantly increase sea turtle catch rates for some species in a small number of studies [109]. There have been inconsistent findings on the effect of the duration of hauling during the daytime on sea turtle catch rates [49,109]. A study in the Hawaii longline tuna fishery found a significant decline in standardized catch rates of blue and oceanic white tip sharks the later in the morning that setting was initiated, and with concomitant smaller duration of hauling during the daytime, likely due to the diel vertical migration cycles of these species and the time of day of gear soak in this fishery [49]. But this observed effect may vary in other areas and fisheries. A lack of access to primary, research grade observer data prevented analyses to determine the effect of time of day of fishing operations and soak time on sea turtle and shark catch rates in the Marshall Islands fishery. Based on survey results, gear is set and soaks throughout the day and into the first half of the night (Table 1a). Total soak times are about 19.5 h, ca. 67% of the gear soak occurs during daylight, and ca. 32% of the haul occurs during daylight (Table 1a). It might be commercially viable for the fishery to reduce the total soak time and duration of hauling during daylight, however, fishery-specific analyses of available observer data should occur first to predict the effects of these changes.

4.8.7. Fishing at submerged features
None of the survey respondents reported fishing at shallow submerged features. Pelagic longline catch rates of vulnerable species have been documented to be higher at shallow seamounts (with summit depths within about 500 m of the surface) relative to open ocean areas [49,172,173].

4.8.8. No lightsticks
The lack of use of lightsticks on branchlines in the fishery, which are used in some longline fisheries to target swordfish and other billfish on shallow-set hooks, likely contributes to avoiding the capture of sea turtles [32,173].

4.9. Opportunities for improved fuel efficiency
Using company records on fuel consumption and for landings, the Marshall Islands fishery consumes 20241 l of fuel per tonne of reported landings. The estimated fuel consumption based on survey responses exceeded but was the same order of magnitude of the estimate calculated from company data (359,678 vs. 262,755 l per year per vessel, respectively). There are few available estimates of fuel consumption per unit wet weight landings for longline fisheries targeting bigeye and yellowfin (Thunnus albacares) tuna [65]. Estimates from 6 longline bigeye and yellowfin tuna fisheries ranged from 1176 to 3660 l of fuel per tonne of wet weight landings, with a mean of 2802 (± 415 SD of the mean) [65,174,175]. This metric of fuel efficiency is likely highly variable between longline bigeye/yellowfin tuna fisheries, and possibly between vessels within an individual fishery, depending on vessel size class, size of the catch, and distance to fishing grounds. Use of the ratio fuel consumption per value of landings may be a more
suitable metric for comparisons between fisheries and between vessels within a fishery. The estimate of average fuel consumption rates did not assess energy consumption for the remainder of the supply chain after the catch is landed. Additional energy expenditure would occur during fish processing, packaging and transport.

The inventory identified the following areas where fuel efficiency could be improved: increase the frequency that vessels are slipped to avoid buildup of hull fouling, repair minor engine oil leaks, use fuel additives, replace older main engines, reduce deck light wattage as practicable and safe, reduce the number of deck lights used during hauling as practicable and safe, and replace older steel hull vessels with modern fiberglass or other lighter materials. A more detailed fuel efficiency assessment could be made by having a professional marine engineer assess other equipment factors of individual vessel’s, including the actual vs. rated fuel consumption of main and auxiliary engines, types of on-board lights and electric motors, propeller size and pitch, and generator sizes and working loads (Bill Holden, Marine Stewardship Council, personal communication, 28 March 2013).

4.10. Next Steps – level 3 ERA

There may be sufficient data quality to conduct a more rigorous, quantitative Level 3 ERA of the fishery. Onboard observer data were collected from 203 trips from 1992 to 2009 (Peter Williams, personal communication, Secretariat of the Pacific Community, 21 February 2013). Depending on the quality of the primary observer program data, which are subject to confidentiality restrictions and were unavailable for use in this study, records could be modeled to determine temporal trends in nominal and standardized catch rates for species with sufficient sample sizes, the latter being an index for local, relative abundance. Analyses could further document trends in catch levels and trends in the proportion of total catch comprised of vulnerable species and groups, the temporal and spatial distribution of catch of vulnerable species to identify any spatially and temporally predictable bycatch hotspots, and identification of the significance of the effect of other factors on standardized catch rates. For example, given adequate data quality, factors could be included in the standardized catch rate model to determine the relative significance of the effect of hook type, and time of day of fishing operations, on sea turtle and elasmobranch standardized catch rates [49,68,116]. Using findings from this ERA and from the proposed standardized catch rate modeling study to identify populations of highest relative risk, subsequent model-based analyses could be undertaken to estimate population-level effects from fishing mortality levels in the Marshall Islands fishery.

Given that there has been no observer data collection since 2009, and evidence of changes in fishing gear and methods since observer coverage was discontinued (change in leader material, discontinued use of surface branchlines and bait to target sharks, time of day of fishing operations, change in retention practices [66,68]), analyses of available observer data would not characterize the contemporary fishery. However, observer coverage in the Marshall Islands fishery is planned to resume in the latter half of 2013 at a 10% coverage rate (personal communication, 6 June 2013, Derrick Wang, Luen Thai Fishing Venture). This renewed monitoring will enable confirmation of fishing gear designs and practices, and with increasing time series length will improve the certainty of findings from fitting the data to a standardized catch rate model.

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