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A PRELIMINARY ECOLOGICAL RISK ASSESSMENT OF THE LARGE-SCALE TUNA LONGLINE FISHERY IN THE EASTERN PACIFIC OCEAN USING PRODUCTIVITY-SUSCEPTIBILITY ANALYSIS

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1. INTRODUCTION

The eastern Pacific Ocean (EPO) supports some of the largest and most valuable tuna fisheries in the world, accounting for 1.17 million (16%) of the global catch of 7.39 million metric tons of tuna and tuna-like species reported in 2015 (FAO 2017). Such large removals of biomass of these target species and their associated bycatch species of billfishes, sharks and large mesopelagic fishes—all of which occupy high trophic levels in oceanic food webs—has the potential to impact the structure and long-term productivity of the supporting pelagic ecosystem, and therefore requires careful management (Kitchell *et al.* 2002; Griffiths *et al.* 2010). Over the past two decades, many fisheries worldwide have broadened the scope of management to include fishery impacts on non-target species and the ecosystem more generally (Pikitch *et al.* 2004; Smith *et al.* 2007). This ecosystem approach to fisheries management is important for maintaining the integrity and productivity of ecosystems while maximizing the utilization of ecosystem assets and services through sustainable fishing practices that do not negatively impact the ecological and biological dynamics of target and non-target species.

The Inter-American Tropical Tuna Commission (IATTC) has adopted an ecosystem-based approach to the management of EPO tuna fisheries through its commitment to ensuring the long-term sustainability of the stocks of tuna and tuna-like species, associated non-target species and the supporting ecosystems through the adoption of the Antigua Convention, in particular Article VII 1(f) "*adopt, as necessary, conservation and management measures and recommendations for species* *belonging to the same ecosystem and that are affected by fishing for, or dependent on or associated with, the fish stocks covered by this Convention…*".

Although ecological sustainability in fisheries is a noble concept, it can be difficult to demonstrate in practice. Detailed information is required on the composition of species impacted by the fishery, their biology and trophic ecology, and fishing mortality in order to parameterize numerical models. The output from these models can help scientists to better understand the direct and indirect effects of fishing and guide fishery managers to implement appropriate management measures to ensure the long-term sustainability of impacted species and their supporting ecosystem. Unfortunately, high-seas pelagic fisheries, especially longline fisheries, frequently interact with a large number of non-target species, many of which are rarely encountered, taxonomically ambiguous, or have low commercial value. As such, many of these species have not been the subject of detailed biological studies, and in many cases, are not reported at the level of species, but only within taxonomic aggregations such as "sharks" and "other fish". Consequently, for most bycatch species there is currently a lack of reliable information required to conduct traditional single-species population assessments to determine their status.

As part of the IATTC's commitment to ecological sustainability and the ecosystem approach to fisheries management, Commission staff has implemented bycatch monitoring programs and conducted key biological and ecological studies to facilitate the parameterization of ecological assessment tools, such as ecosystem models (Olson and Watters 2003). However, acquiring the data required to populate models that can be used for tactical fisheries management will take many years and significant resources, but in the meantime the Commission is mandated by the Convention to demonstrate ecological sustainability in its management measures. Consequently, assessment approaches are required for data-limited fisheries and species that can rapidly assess the key risks within a fishery that can be prioritized for further data collection, assessment, mitigation, or management.

Ecological Risk Assessment (ERA) is one such approach that can be effective for assessing the sustainability of data-limited fisheries that interact with speciose assemblages. ERA is a suite of flexible tools that can be adapted to fisheries to make use of available data types to focus on issues of interest, ranging from social wellbeing to entire ecosystems. ERA approaches range from qualitative likelihood–consequence scoping methods driven by stakeholder involvement (Fletcher 2005) to quantitative spatially explicit assessment models (Zhou and Griffiths 2006). Hobday *et al.* (2011) described the ERA process for fisheries as a spectrum of increasing assessment complexity from "Level 1" (scoping and qualitative assessment of major risks) to "Level 3" (quantitative assessment of individual species or communities) as knowledge of fishery impacts improves over time by addressing risks to key species with improved data – through targeted research or improved fishery data reporting – or mitigation by removing or reducing key threatening processes (Figure 1). "Level 2" of this process is suited to more developed fisheries that may be data-limited, particularly for non-target species, but for which sufficient data are available to use semi-quantitative methods to facilitate prioritizing species that may be vulnerable of becoming unsustainable under current levels of fishing.

A number of semi-quantitative attribute-based ecological risk assessment methods have been developed to assess the relative sustainability of individual species impacted by fisheries. These include fuzzy logic expert systems (Cheung *et al.* 2005), qualitative risk matrices (Astles *et al.* 2006) and productivity-susceptibility analysis (PSA) (Milton 2001; Stobutzki *et al.* 2001). PSA has been widely used in data-poor fisheries, as it has the flexibility of using various data types to rapidly produce a relative measure of vulnerability of a large number of species that can be easily interpreted by fishery managers, policy makers, and laypersons. As a result, PSA is the primary ERA method recommended by the Marine Stewardship Council for fisheries seeking certification for ecolabeling purposes (MSC, 2010).

PSA operates by ranking each species documented to be impacted (either directly or indirectly) by a fishery on a number of attributes relating to its susceptibility to being captured, and its capacity to recover should the population become depleted. For each species, susceptibility attributes (*e.g.*

geographic distribution relative to fishing effort) and recovery attributes (*e.g.* growth rate and fecundity) are given a rank of 1 (least susceptible; least productive) to 3 (most susceptible; most productive). The scores for susceptibility and productivity attributes for each species are averaged, and then combined to produce an overall vulnerability score from 0 (least vulnerable) to 3 (most vulnerable). The species with the highest ranks across all attributes are then considered most vulnerable to becoming unsustainable under current levels of fishing.

Vulnerability in an ecological risk assessment context can be defined as the potential for the productivity of a stock to be diminished beyond expected natural fluctuations by direct and/or indirect fishing impacts. Unlike stock assessments of target species, PSA—and most ERA approaches—does not provide robust population status estimates against biological reference points; its primary function is to act as a data-driven 'filter' to prioritize species for further research or management intervention that will mitigate the risk of population decline for vulnerable species. An example is the use of the back-down procedure to encourage escapement of dolphins in the EPO tuna purse-seine fishery.

The IATTC staff has recently developed a preliminary PSA to estimate the vulnerability of non-target species caught in the purse-seine fishery (Class 6 vessels only) in the EPO (SAC-07-07b) with the intention of extending the approach to other tuna fisheries, particularly the large-scale tuna longline fishery, following the requests by some IATTC Members (Page 26 in IATTC, 2015). A recent metadata analysis of longline data held by the IATTC (SAC-08-07b) indicated substantial data quality and reporting issues that have hindered a comprehensive ERA of the EPO longline fishery. However, after methodological improvements of the PSA model (SAC-08-07c), it was considered sufficiently flexible for a preliminary assessment of the longline fishery, using the available data, that would identify potentially vulnerable species and help guide the Commission in developing appropriate measures and/or prioritizing future research to address sustainability concerns.

This paper describes a preliminary PSA for the large-scale tuna longline fishery in the EPO, identifies key data deficiencies, and makes recommendations for enhancing data collection that would improve the reliability of outcomes from future assessments.

2. METHODOLOGY

2.1. Definition of the fishery

The IATTC Convention Area extends over an area of approximately 55 million km^2 from the west coast of the Americas to 150°W between latitudes 50°N and 50°S. The fisheries that operate in the area, both within and outside national Exclusive Economic Zones (EEZs), include a wide variety of vessel sizes, gear configurations, and target species, which makes clear definitions of fisheries problematic. The longline fishery in the EPO is particularly difficult to define, since vessels range from large industrial vessels of up to 91.5 m length overall (LOA), with hydraulic line haulers and large refrigerated fish holds that undertake fishing trips lasting for up to several months (SAC-08-07b), to small artisanal vessels of less than 10 m LOA using hand-hauled gear in neritic waters during fish trips that last for 2-3 days (Andraka *et al.* 2013; Martínez-Ortiz *et al.* 2015; Aires-da-Silva *et al.* 2016; Siu and Aires-da-Silva 2016).

Originally, the industrial longline vessels operating in the EPO were from Far Eastern nations (Japan, Korea, China, and Chinese Taipei), and were usually referred to as the 'distant-water' fleet. They fish far from land for months or years at a time, primarily targeting tunas and billfish. However, since the mid-1990s vessels from the United States, French Polynesia, Vanuatu and Belize have operated in the fishery, invalidating the 'distant-water' classification. In Resolution C-03-07, the IATTC classified longline vessels over >24 m LOA as "large-scale tuna longline fishing vessels" (LSTLFVs). All vessels authorized to fish for tuna and tuna-like species in the EPO are required to be included in the IATTC Regional Vessel Register, and Resolution C-11-08 requires that at least 5% of the fishing effort (defined as days fishing) by longline vessels over 20 m LOA carry a scientific observer.

In contrast, the smaller artisanal longliners from EPO coastal CPCs target a broader complex of large pelagic species—mainly sharks, tunas, billfish and dorado *Coryphaena hippurus*—and their spatial distribution can extend beyond coastal waters (see Aires-da-Silva *et al*., 2016; Siu and Aires-da-Silva, 2016). For example, there is a growing "oceanic-artisanal" fleet that fishes the high seas in small vessels, with assistance from motherships, targeting tuna, billfish, and sharks as far from the coast to offshore waters as far as 100°W (Andraka *et al*., 2013; Martínez-Ortiz *et al*., 2015). Because the fishing vessels are less than 24 m LOA they are not required to conform to Resolution C-03-07 and be included on the IATTC LSTLFV List, or carry a scientific observer aboard, per Resolution C-11-08.

The ecological risk assessment presented in this paper draws upon the logbook and scientific observer data submitted to the IATTC by its Members under Resolutions C-03-05 and C-11-08 and described in Document SAC-08-07b. Therefore, for consistency with the terminology in Resolution C-03-07, the assessment is restricted to the fishery conducted by LSTLFVs, which for simplicity is referred to as the "longline fishery".

2.2. Spatial extent of the analysis

One of the key components of the PSA approach is to determine the susceptibility of each species to being captured by a fishery (Stobutzki *et al.* 2001). The first step towards assessing susceptibility is to determine the extent of overlap of fishing effort with the geographic distribution of a species. In other words, if the majority of fishing effort overlaps with only a small proportion of the species' distribution, the species can be deemed to have a low susceptibility to capture, regardless of how effective the gear may be for capturing that species.

Although the IATTC Convention Area extends over an area of 55 million km^2, annual longline fishing effort is not evenly distributed across this area. As such, there may be significant spatial refuge from fishing for wide-ranging species. Furthermore, effort distribution has varied substantially between years, particularly over the past decade (SAC-08-07b). In exercising the precautionary principle, as required by Article IV of the Antigua Convention, we cannot assume that current effort patterns will remain static, or that historical patterns will not recur. As such, we defined the spatial extent of the fishery as the maximum extent of historical fishing effort, which effectively means that the fishery extended to the extremities of the IATTC convention area, as effort has been recorded in almost every 5°x5° square over the fishery's history (Figure 2). This approach may positively bias the potential encounterability of the fishery by bycatch species, and potentially create false positives of species that may be classified as being highly vulnerable. However, this precautionary approach is required until more reliable fishery data are obtained. We somewhat tempered the propensity for false positives under this assumption by dividing the EPO into five primary fishing areas defined by Hinton (2003), which allowed for some spatial refuge for species having a strong affinity for neritic (*e.g.* Indo-Pacific sailfish) or temperate (*e.g.* salmon and porbeagle sharks) waters.

2.3. Data available for the assessment

There is a paucity of published information on the suite of species with which the EPO longline fishery interacts. Although there are comprehensive species lists published for artisanal longline fisheries in countries in the EPO, including Ecuador (Martínez-Ortiz *et al.* 2015), Peru (Alfaro-Shigueto *et al.* 2010), Panama, Costa Rica (Andraka *et al.* 2013), and other Central American CPCs[2] (Siu and Aires-da-Silva 2016), most fishing effort in these studies was distributed in coastal waters, using gear configurations different from those used by the LSTLFVs. We were not confident that the data from these fisheries were representative of the EPO large-scale tuna longline fishery, and thus did not include them in our assessment. However, it is recommended that future ecological risk assessments of pelagic longline fisheries in the EPO include the artisanal fisheries. Data from the artisanal fisheries could be incorporated into the analysis, or, since those fisheries interact with a different suite of species with different susceptibility attributes, operate in neritic habitats, use different gear configurations, and

[2] Members and Cooperating Non-Members of the IATTC

target smaller species such as dorado (Martínez-Ortiz *et al.* 2015; Siu and Aires-da-Silva 2016), they could be analyzed separately.

Given the lack of published catch information, we undertook a metadata analysis of the catch and effort data held by the IATTC (see SAC-08-07b) to build a list of species with which the longline fishery interacts and generated distributional information, based on the average annual nominal CPUE from 1954-2015, to guide the scoring of spatial susceptibility attributes. After discovering a range of data deficiencies and reporting issues in the metadata analysis, we supplemented the list of species reported in the IATTC database with additional species recorded in the annual reports submitted to the IATTC by the national longline observer programs.

2.4. Taxa not included in the assessment

PSA is a tool that facilitates the process of prioritizing taxa of potential concern based on their susceptibility to being captured by a specific gear type and the capacity of their populations to withstand, or recover from, fishing impacts. The highest-risk species are dealt with in one of two ways: either the risk is mitigated through management intervention or, if the risk cannot be mitigated, the species becomes the focus of more intensive research to collect higher-quality biological and/or catch data, so that the population's status can be assessed using more sophisticated population models.

Several species of seabirds, sea turtles, and marine mammals have long been considered to be at high risk of becoming unsustainable due to direct mortality from longline fishing (Gilman *et al.* 2006; 2007; Anderson *et al.* 2011). As a result, these species groups are included in observer programs in the EPO and some species are subject to periodic population assessments pursuant to IATTC Resolutions C-03-10, C-11-02, and C-11-08. Furthermore, SAC-08-07b noted that data relating to seabird, sea turtle, and marine mammal captures or interactions have not been provided to the IATTC, and they are generally only briefly mentioned in CPC annual reports. As such, these species groups are not included in our PSA assessment of the longline fishery, which focuses on teleost and elasmobranch species.

There were many records in the IATTC database and annual CPC observer reports where catches were reported as taxonomic aggregations (*e.g.* "Elasmobranchii"). The aggregations of Carcharhinidae, Elasmobranchii, Istiophoridae/Xiphiidae, *Isurus* spp., Osteichthyes, and Thunnini were omitted from the dataset, as they can include several species with different susceptibility and/or productivity attributes and scores.

2.5. Attribute scoring

The attribute based approach of assessing the vulnerability of a species to fishing using productivity and susceptibility constructs has taken on various forms, depending on the fishery or species of interest. For example, Patrick *et al.* (2009) used a different weighting system to score attributes relating to productivity and susceptibility constructs and then averaged the scores to produce an overall vulnerability index. In contrast, Walker (2004) combined productivity and susceptibility attributes that were adapted to elasmobranchs to produce a vulnerability score, using a multiplicative approach.

A recent PSA developed by IATTC staff for the EPO purse-seine fishery (SAC-07-07b) used the approach of Patrick *et al.* (2009), using nine productivity and eight susceptibility attributes. In order to make the results for the purse-seine and longline fisheries comparable, we used the same approach. However, we removed the weighting system and reduced the number of attributes, because sensitivity analyses confirmed that several productivity attributes were autocorrelated (SAC-08-07b).

In our analysis, we determined the relative vulnerability of species caught in the longline fishery based on six susceptibility attributes, which describe the susceptibility of a species to capture and mortality by fishing, and five productivity attributes, which describe the capacity of a population to withstand, or recover from, fishing mortality. For each species, susceptibility and productivity attributes are scored on a scale of 1 (least susceptible; least productive) to 3 (most susceptible; most productive). As a precautionary approach, the lowest possible score (1 and 3 for productivity and susceptibility, respectively) was assigned to an attribute for species for which no information was available, or a closely related species.

For each species, an overall susceptibility (*s*) and productivity (*p*) score was computed by averaging attribute scores, and was plotted on a two-dimensional graph. The *s* and *p* scores were then combined to produce an overall vulnerability score (*v*) from 0 (least vulnerable) to 3 (most vulnerable) using the following model:

$$v = \sqrt{(p-3)^2 + (s-1)^2}$$

Species having a *v* score of <1, 1-2, or >2 were classified as having low, medium, or high relative vulnerability, respectively. It is important to note that this approach produces a relative measure of vulnerability under current levels of fishing. Below we briefly describe the susceptibility and productivity attributes used in the PSA: the specific scoring thresholds for productivity and susceptibility are detailed in Tables 1 and 2, respectively.

2.6. Susceptibility attributes

2.6.1. Areal overlap

This attribute describes the extent of geographic overlap of fishing effort with the distribution of an impacted species. The geographic extent of the longline fishery in the EPO was defined using the spatial distribution of effort over the history of the fishery (Figure 2). Species distributions were estimated using reported catch data and supplemented with known occurrences documented in FishBase (Froese and Pauly 2017). The extent of overlap is determined by the number of occurrences of a species within the five longline effort areas defined by Hinton (2003).

2.6.2. Seasonal availability

This attribute describes the proportion of a year that a species is available for interaction with the longline fishery. Some species may undertake seasonal migrations out of the EPO, and thus are not available for capture by the longline fishery.

2.6.3. Aggregation behavior

Several species of pelagic fishes form large schools, which potentially makes a larger proportion of the population more susceptible to capture when encountering fishing gear. Scores reflect the degree to which a species normally aggregates, either naturally or in reaction to gear (*e.g.* attraction to fish or squid baits used in the longline fishery), and thus increase the potential for large catches in a set.

2.6.4. Encounterability

Encounterability defines the extent of overlap of a species' depth range with the normal depth range of the fishing gear. Although a species may be distributed within areas where longline effort is high, it may not be susceptible to capture if its vertical distribution does not overlap with the depth of the gear. Estimating encounterability in longline fisheries can be problematic, since the depth of the gear differs depending on the target species, and a species' behavior can vary depending on the time of day. For example, bigeye tuna is often targeted by deploying the gear during the day below the thermocline to depths of around 300 m, whereas swordfish are generally targeted at night with shallow sets of less than 200 m (Boggs 1992; Ward and Myers 2005). Also, shallow sets are more likely to catch mesopelagic species since many undertake vertical migrations to the mixed layer at night.

Unfortunately, the majority of CPCs do not provide operational-level data or information on target species with the catch and effort data they are required to submit to the IATTC under Resolution C-03-05, which severely hindered our ability to determine the effective fishing depth of the gear. However, the metadata review of EPO longline data held by the IATTC (SAC-08-07b) showed that since about 1995 there has been an increasing trend in the nominal CPUE of swordfish, sharks, and bycatch species, but a declining CPUE of tunas, particularly bigeye. In the absence of operational-level information, these data suggest, *prima facie*, that the majority of sets are likely to be shallow deployments at night, when swordfish and a larger number of mesopelagic bycatch species are near the surface. Therefore, given the available data and applying a precautionary approach, we assumed that longlines fished to a maximum depth of 200 m, which covers the typical depth range of shallow pelagic longlines deployments (Bigelow *et al.* 2006).

2.6.5. Gear selectivity

The selectivity of the longline gear describes the potential for a species to be hooked once it has encountered the gear. Branchlines used on longlines in the EPO are generally fitted with large heavy-gauge hooks (8/0 to 10/0) and baited with squid or fish (*e.g.* mackerel), to target large tunas, billfish, and sharks (Bigelow *et al.* 2006). Therefore, selectivity is first determined by the desirability of the bait to a species, followed by the mouth gape of the species, which ultimately determines its potential for being hooked. Therefore, smaller species, and juveniles of larger species, have a reduced potential for being hooked.

2.6.6. Post-capture survival

Once a fish is hooked and brought onboard or alongside the vessel, there is still the potential for the fishery to have a negligible impact on a species population if the fish is released and has a high probability of survival after release. The potential for survival depends on the desirability of the species (obviously target species are unlikely to be released), the degree to which a species can tolerate the stress of being hooked and then handled during the release process, the potential for scale loss and appendage damage while hooked and during the release process, and the physiological ability to tolerate surfacing from, and returning to, deep water (*i.e.* barotrauma).

2.7. Productivity attributes

We took a hierarchical precautionary approach to assigning scores for productivity attributes. For each species assessed, we first attempted to obtain species-specific values for each attribute from IATTC data or published studies for the EPO, or at least the Pacific Ocean. Where no species-specific values could be found, a value for similar species from the same genus or family from FishBase (Froese and Pauly 2017) was used. Where no value could be found for the species or a similar species, a precautionary score of 1 was used.

2.7.1. Maximum size

Maximum size of a species was used as an indicator of relative recovery rate. Larger species are generally long-lived and grow slowly (Froese and Binohlan 2000), thus their population is expected to recover more slowly after depletion than a species with a short life span. Species-specific information was obtained from maximum recorded length in FishBase (Froese and Pauly 2017), the International Game Fish Association all-tackle records (IGFA, 2014), and the literature.

2.7.2. von Bertalanffy growth coefficient (*K*)

The von Bertalanffy growth function (VBGF) is one of the most widely applied models for describing the growth dynamics of fishes. Of the three parameters in the model, K—also known as the Brody growth rate coefficient—describes the average rate at which a population approaches the length-at-infinity (L_∞; the average length of an individual if members of the population lived indefinitely). Higher values of K (>0.3) for a species generally indicate that its population is highly productive and could recover more rapidly after depletion from fishing.

2.7.3. Fecundity

Fecundity refers to the total number of viable offspring or oocytes produced annually by a species. Species that are that produce many thousands of oocytes per year (*e.g.* skipjack tuna) have a higher potential for sustaining recruitment into the population, or recovering from fishing impacts, than species that produce a small number of offspring, sometimes only every few years (*e.g.* some sharks).

2.7.4. Breeding strategy

Breeding strategy describes the relative level of investment that a species places on the wellbeing of early life stages of its offspring. The two extremes of the breeding strategy spectrum are broadcast spawners, like tunas, which spawn several times per year and exhibit no parental care, and species that have high parental investment and produce a small number of live young each year, or every few years (*e.g.* some sharks). Species that reproduce frequently have a higher capacity to recover from fishing impacts than species that spawn infrequently and direct a lot of energy towards parental investment.

2.7.5. Age at maturity

The age at which a species reaches sexual maturity plays a large role in a population's capacity to recover from depletion caused by fishing. Generally, species that take many years to reproduce are also slow-growing and long-lived, meaning that even modest fishing mortality may make their populations unsustainable. There are several ways to determine age at maturity; such as the age at which the youngest individual is mature (A_{MAT}), or the age at which 50% of the population is mature (A_{50}).

3. RESULTS

In total, 68 species were found to have some level of interaction (captured, discarded, or impacted) with the longline fishery in the EPO (Table 3). Of these, 38 species were derived from the IATTC database, while the remaining 30 were recorded in annual CPC observer reports.

Of the 68 species assessed, 12, 38 and 18 species were classified as having low, moderate, and high vulnerability, respectively. Of the 18 highly vulnerable species, 13 were elasmobranchs. Results of the PSA are shown in Figure 3 and Table 3, disaggregated by the principal tuna and billfish species, elasmobranchs, tuna-like species, and mesopelagic fishes.

All 12 principal tuna and billfish species had vulnerability (*v*) scores exceeding 1, with five species (albacore, Pacific bluefin, and yellowfin tunas, swordfish, and striped marlin) being classified as highly vulnerable (Figure 3a). Of this group, Pacific bluefin tuna and swordfish had the highest *v* score (2.06), as these species both had high susceptibility to capture and low productivity, as a result of their longevity and late maturity.

Of the 23 elasmobranch species, 13 had a *v* score greater than 2.00 and were classified as highly vulnerable. Four of these species (bigeye thresher, tiger, porbeagle and blue sharks) shared the highest *v* score of the assessment (2.33) (Table 1), due to very low productivity scores (1.00-1.80) and high susceptibility scores (2.20-3.00). The remaining 10 species were classified as moderately vulnerable, mainly due to high susceptibility scores (*v* >2.00), although silky and oceanic whitetip sharks could be considered highly vulnerable, since they had *v* scores of 1.98.

Tuna-like species were represented by 12 taxa, with six species classified as being moderately vulnerable, although three—wahoo, and the two species of dolphinfish—had *v* scores of 1.80, which placed them in close vicinity to being highly vulnerable. All tuna-like species had very high productivity values (*p* >2.80), indicating that their vulnerability was driven by their high susceptibility to capture (Figure 3c).

Of the 21 species of mesopelagic fishes assessed, 15 were classified as being moderately vulnerable, although snake mackerel approached the highly vulnerable category with a *v* score of 1.84.

4. DISCUSSION

Ecological sustainability has become an increasingly important component of fisheries management policy in recent years, in recognition of growing evidence that even biologically sustainable fishing impacts on target species can have significant impacts on the dynamics of the supporting ecosystem. The potential for large-scale tuna fisheries to disrupt ecological processes in pelagic ecosystems such as that of the EPO is significant, given that these fisheries interact with species occupying high trophic levels that play a significant role in regulating the structure of ecosystems through 'top-down' predatory control (Heithaus *et al.* 2008; Polovina *et al.* 2009). Although an aspiring goal, demonstrating the ecological sustainability of fishing is problematic, despite the availability of sophisticated tools and models that are now capable of capturing the complexity of marine ecosystems (Pauly *et al.* 2000; Fulton *et al.* 2004). The primary problem is the paucity of reliable biological, ecological, and species-specific catch information for many species of low economic value, especially in tropical regions where species richness is often high.

The productivity-susceptibility analysis detailed in this paper attempted to overcome some of the current data limitations and provide a preliminary assessment of the ecological sustainability of finfish and elasmobranchs impacted by the EPO large-scale tuna longline fishery. Employing such a rapid, flexible and cost-effective ecological risk assessment approach allows the most pressing sustainability issues in data-limited fisheries to be identified, and thus then mitigated or investigated further. However, the trade-off in using semi-qualitative data is that PSA produces only a relative indicator of vulnerability for impacted species. and does not provide a quantitative measure of population sustainability.

4.1. Potentially vulnerable species

Using the limited dataset available, at least 18 species were considered highly vulnerable to becoming unsustainable under the current longline fishing regime in the EPO. Without quantitative population assessments, it remains unclear whether these 18 species are truly at risk Moreover, some, or possibly all, of the 37 moderately vulnerable species may in fact be currently unsustainable, but again, it is impossible to ascertain their status in the absence of reliable biological and longline catch data (see SAC-08-07b).

Nonetheless, the PSA provides valuable insights into the relative vulnerability of species caught by the fishery. The high vulnerability of tunas and billfish may not be particularly surprising, considering they are the primary targets of the fishery. Within a broader ecological risk assessment framework, such as the Ecological Risk Assessment for the Effects of Fishing (ERAEF) approach developed by Hobday *et al.* (2011) (Figure 1), high-risk species would require immediate management action, to either collect additional information to improve the reliability of the assessment, or introduce management measures to mitigate the risks. However, all of these species are the subject of ongoing species-specific monitoring in EPO fisheries and regular, or at least periodic, stock assessments (see Hinton 2003; Aires-da-Silva and Maunder 2013; Minte-Vera *et al.* 2015), and therefore immediate management attention is not required unless the more sophisticated population models indicate a sustainability issue, or if other issues become apparent regarding the reliability of monitoring data. For example, although billfish catches by large purse-seine vessels (Class 6) in the EPO are monitored by on-board observers, there has been concern over the reliability of the identification of marlins (SAR-15-9). Periodic reviews using the risk assessment framework allows such issues to be identified and rectified; in the case of billfish, with improved billfish identification guides and observer training.

A particular concern arising from the PSA results was the large number of elasmobranch species that were classified as moderately or highly vulnerable, in particular silky, oceanic whitetip, and the three species of thresher sharks. This provides strong evidence that these species require urgent management attention, despite the specific IATTC resolutions adopted for some of these species. For example, Resolution C-11-10 prohibits the retention of oceanic whitetip sharks, but since the species is taken as bycatch, it is unlikely that the fishing mortality on this species has changed significantly since the resolution entered into force in 2012—assuming there has been no substantial change in gear configurations. The IATTC also adopted Resolution C-16-06 on the conservation of silky sharks, which limits the proportion of sharks to total trip catch by longline vessels to 20%. However, there are no other harvest controls for the diverse suite of sharks caught in the longline fishery, other than Resolution C-05-03, which encourages the full utilization of sharks and a 5% ratio of shark fins to the total retained shark catch.

The bigeye thresher shark (*Alopias superciliosus*) had the highest vulnerability score in the current PSA, and was also identified as the most vulnerable species in the purse-seine fishery (SAC-07-07b). A recent Pacific-wide assessment of the species estimated that less than 5% of the population was impacted by fishing, but this still exceeded the maximum biologically sustainable threshold in some years (Fu *et al.* 2016). Such evidence indicates that many of the shark species caught in the longline fishery may still be highly vulnerable to overfishing, despite the specific conservation and management measures. Although the IATTC staff has attempted to assess the stock of silky sharks in the EPO (Aires-da-Silva *et al.* 2014), unfortunately there are currently insufficient data to produce a reliable indicator of stock status.

A particularly interesting outcome of the PSA was the large number of mesopelagic and tuna-like species that were classified as moderately vulnerable. The life histories of the majority of these species are poorly understood, even for those that are frequently caught and retained for sale, such as escolar, oilfish, opah, and pomfrets. Many of these species occupy deep cool waters below the thermocline (Gray 2016), and therefore may be slow-growing, long-lived, and mature late in life, like many temperate deep-sea fishes (see Smith *et al.* 1995; Horn and Hurst 1999). Therefore, specific life history studies of these species are recommended. to better understand their potential vulnerability to becoming unsustainable due to fishing.

4.2. Considerations for future work

There are several areas where future ecological risk assessment of the EPO longline fishery can be improved by the use of more reliable catch and effort data, which may already be collected by the observer programs of CPCs, but are not submitted to the IATTC in their entirety (SAC-08-03d). There is currently great uncertainty about the encounterability of gear used in typical longline sets in the EPO, due to the absence of operational-level data for the majority of CPCs. The data submitted by CPCs show increases in the CPUE of swordfish and epipelagic fish and in bycatches of sharks, which indicates, *prima facie*, that the EPO longline fishery primarily makes shallow sets at night (see SAC-08-07b). As a result, a large number of mesopelagic species were classified as being moderately vulnerable owing to their nocturnal migrations to the mixed layer (Kerstetter *et al.* 2008; Gray 2016). Set-by-set operational level data, including gear configurations, would greatly improve our ability to determine the overlap of the gear depth with the vertical distribution of these and other species. Furthermore, set-by-set data and improved species-specific reporting of bycatch species would allow researchers to work with finer scale data to better estimate the extent of spatial overlap of fishing effort with the distribution of impacted species. Such data would be required if moving to an ecological risk assessment approach in future that can provide a quantitative measure of risk.

One such approach is a new spatially-explicit quantitative model named Sustainability Assessment for Fishing Effects (SAFE), which assesses risk in relation to well-established biological reference points (Zhou and Griffiths 2008). Although there are several methodological adjustments that may need to be made to adapt the method to high-seas tuna fisheries, SAFE has great potential to be a more reliable approach for producing rapid and low-cost quantitative ecological risk assessments. Given the spatially-explicit nature of SAFE, it may also be possible to operationally couple SAFE with the same management strategies assessed for single species in stock assessments. This will allow the IATTC to make significant steps towards formally integrating ecosystem components into its management framework, to conform to the mandates of the Antigua Convention related to ecological sustainability. However, SAFE relies heavily on fine-scale species distribution maps to determine the extent of overlap with fishing effort, and this may affect the feasibility of using it for the EPO.

Finally, the PSA did not consider the cumulative impacts of other EPO fisheries, such as the purse-seine fishery, the diverse artisanal fisheries that extend from the neritic regions to the high-seas, and even fisheries outside the EPO that fish cosmopolitan stocks. These are important considerations in assessing the viability of populations in the EPO, and require dedicated data collection programs for all EPO fisheries that record not just catches, but also their species composition and spatial distribution, similar to what is currently underway for the coastal artisanal longline fleet in the EPO (SAC-08-06a(ii). With the availability of such data, IATTC scientists could develop methods that can quantitively assess the cumulative impacts of fishing on species and communities that are the responsibility of the IATTC.

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TABLE 1. Susceptibility attributes and scoring thresholds used in the productivity-susceptibility analysis for the large-scale tuna longline fishery in the eastern Pacific Ocean.

Susceptibility attribute	Ranking		
	Low (1)	Moderate (2)	High (3)
Areal overlap			
Extent of geographic overlap of the fishery with the primary distribution of the species	Species reported to be caught in <2 high-effort areas in the IATTC Convention Area.	Species reported to be caught in 2-3 high-effort areas in the IATTC Convention Area.	Species reported to be caught in >3 high-effort areas in the IATTC Convention Area.
Seasonal availability			
The proportion of a year that a species is available for potential interaction with the fishery.	Low availability due to the species being present in the IATTC Convention Area for less than 3 months of the year.	Medium availability due to the species being present in the IATTC Convention Area for 3-6 months of the year.	High availability due to the species being present in the IATTC Convention Area for more than 6 months of the year.
Aggregation behavior			
The degree to which a species normally aggregates, either naturally or in relation to gear type (*e.g.* attraction to bait)	Solitary species, and/or not attracted to baits on longlines.	Normally found in loose aggregations, and/or has some attraction to baits on longlines.	Normally schooling species, and/or highly attracted to baits on longlines.
Encounterability			
The position of the species within the water column relative to the fishing depth of the gear.	Low overlap with fishing gear. Majority of the stock distributed above or below the normal depth of the gear.	Medium overlap with fishing gear. A reasonable portion of the stock distributed within the normal depth of the gear.	High overlap with fishing gear. Majority of the stock distributed within the normal depth of the gear. Default score for target species (P1)
Gear selectivity			
Potential for the gear to retain a species once an interaction has taken place.	Small proportion of the stock that encounters the gear is hooked.	Medium proportion of the stock that encounters the gear is hooked.	Large proportion of the stock that encounters the gear is hooked. Default score for target species (P1).
Post-capture survival			
Potential for a species to survive after being caught and released.	Highly robust species, with high potential for post-capture survival.	Reasonably robust species, with some potential for post-capture survival.	Delicate species, with low potential for post-capture survival due to trauma, scale loss, etc.

TABLE 2. Productivity attributes and scoring thresholds used in the productivity-susceptibility analysis for the large-scale tuna longline fishery in the eastern Pacific Ocean.

Productivity attribute	**Ranking**		
	Low (1)	**Moderate (2)**	**High (3)**
Maximum size (cm)			
Maximum recorded size of a species, in cm.	> 350	> 200, ≤ 350	≤ 200
von Bertalanffy growth coefficient (*K* yr^{-1})			
The Brody growth rate coefficient describing the rate at which a population approaches the average length of an individual if fish lived indefinitely (L_∞).	< 0.1	0.1–0.3	> 0.3
Fecundity			
The total number of viable offspring (or oocytes) that a fish produces annually.	< 10	10–200,000	> 200,000
Breeding strategy			
The relative investment by a species in the wellbeing of early stages of its offspring's life; assessed by Winemiller's index of parental investment (0–14).	≥ 4	1 - 3	0
Age at maturity (years)			
The age (in years) at which 50% of the population is mature (A_{50}).	≥ 7.0	≥ 2.7, < 7.0	< 2.7

TABLE 3. Species included in the productivity-susceptibility analysis for the large-scale tuna longline fishery in the eastern Pacific Ocean, showing average productivity (*p*) and susceptibility (*s*) scores used to compute the overall vulnerability score (*v*) for each species, rated as low (green), medium (yellow), and high (red). See footnote for primary information sources.

TABLA 3. Especies incluidas en el análisis de productividad-susceptibilidad de la pesquería atunera palangrera a gran escala en el Océano Pacífico oriental. indicado las puntuaciones promedio de productividad (*p*) y susceptibilidad (*s*) usadas para calcular la puntuación general de vulnerabilidad (*v*) para cada especie, clasificada como baja (verde), mediana (amarillo), y alta (rojo). Ver nota al pie para las fuentes principales de información.

Group	Family	Scientific name	Common name	FAO code	Source	*p*	*s*	*v*
Grupo	**Familia**	**Nombre científico**	**Nombre común**	**Código FAO**	**Fuente**	***p***	***s***	***v***
Billfishes	Istiophoridae	*Istiompax indica*	Black marlin	BLM	1	2.00	2.60	1.89
		Istiophorus platypterus	Indo-Pacific sailfish	SFA	1	2.40	2.80	1.90
		Kajikia audax	Striped marlin	MLS	1	2.60	3.00	2.04
		Makaira nigricans	Blue marlin	BUM	1	2.20	2.60	1.79
		Tetrapturus angustirostris	Shortbill spearfish	SSP	1	2.40	2.60	1.71
	Xiphiidae	*Xiphias gladius*	Swordfish	SWO	1	2.00	2.80	2.06
Tunas	Scombridae	*Katsuwonus pelamis*	Skipjack	SKJ	1	3.00	2.60	1.60
		Thunnus alalunga	Albacore	ALB	1	2.80	3.00	2.01
		Thunnus albacares	Yellowfin tuna	YFT	1	3.00	3.00	2.00
		Thunnus maccoyii	Southern Bluefin tuna	SBF	1	2.40	2.40	1.52
		Thunnus obesus	Bigeye tuna	BET	1	2.40	2.80	1.90
		Thunnus orientalis	Pacific Bluefin tuna	PBF	1	2.00	2.80	2.06
Elasmobranchs	Alopiidae	*Alopias pelagicus*	Pelagic thresher shark	PTH	1	1.00	2.00	2.24
		Alopias superciliosus	Bigeye thresher shark	BTH	1	1.00	2.20	2.33
		Alopias vulpinus	Common thresher shark	ALV	2	1.40	2.20	2.00
	Carcharhinidae	*Carcharhinus albimarginatus*	Silvertip shark	ALS	3	1.60	2.00	1.72
		Carcharhinus falciformis	Silky shark	FAL	1	1.60	2.40	1.98
		Carcharhinus galapagensis	Galapagos shark	CCG	4	1.60	2.00	1.72
		Carcharhinus limbatus	Blacktip shark	CCL	1	1.80	2.20	1.70
		Carcharhinus longimanus	Oceanic whitetip shark	OCS	1	1.60	2.40	1.98
		Galeocerdo cuvier	Tiger shark	TIG	5	1.00	2.20	2.33
		Prionace glauca	Blue shark	BSH	1	1.80	3.00	2.33
	Dasyatidae	*Pteroplatytrygon violacea*	Pelagic stingray	PLS	1	1.80	2.00	1.56
	Lamnidae	*Isurus oxyrinchus*	Shortfin mako shark	SMA	1	1.40	2.60	2.26
		Isurus paucus	Longfin mako shark	LMA	1	1.20	2.40	2.28
		Lamna ditropis	Salmon shark	LMD	5	1.20	2.20	2.16
		Lamna nasus	Porbeagle shark	POR	1	1.00	2.20	2.33
	Odontaspididae	*Odontaspis noronhai*	Bigeye sand tiger shark	ODH	5	1.00	1.60	2.09

Group	Family	Scientific name	Common name	FAO code	Source	*p*	*s*	*v*
Grupo	Familia	Nombre científico	Nombre común	Código FAO	Fuente	*p*	*s*	*v*
	Pseudocarchariidae	*Pseudocarcharias kamoharai*	Crocodile shark	PSK	2	1.40	1.60	1.71
	Sphyrnidae	*Sphyrna lewini*	Scalloped hammerhead shark	SPL	1	1.40	2.60	2.26
		Sphyrna mokarran	Great hammerhead	SPK	2	1.40	2.40	2.13
		Sphyrna zygaena	Smooth hammerhead	SPZ	6	1.40	2.60	2.26
	Squalidae	*Isistius brasiliensis*	Cookie cutter shark	ISB	2	2.00	1.20	1.02
		Squalus acanthias	Picked dogfish, Spiny dogfish	DGS	1	1.40	1.60	1.71
		Zameus squamulosus	Velvet dogfish	SSQ	2	1.40	1.20	1.61
Mesopelagic fishes	Alepisauridae	*Alepisaurus brevirostris*	Short snouted lancetfish	ALO	5	3.00	2.60	1.60
		Alepisaurus ferox	Long snouted lancetfish	ALX	1	3.00	2.60	1.60
	Bramidae	*Eumegistus illustris*	Brilliant pomfret	EBS	3	2.80	2.00	1.02
		Taractes asper	Rough pomfret	TAS	5	2.80	2.00	1.02
		Taractichthys steindchneri	Sickle Pomfret	TST	5	2.80	1.80	0.82
	Gempylidae	*Gempylus serpens*	Snake mackerel	GES	1	2.60	2.80	1.84
		Lepidocybium flavobrunneum	Escolar	LEC	1	2.20	2.20	1.44
		Nesiarchus nasutus	Black gemfish	NEN	5	2.60	1.80	0.89
		Promethichthys prometheus	Roudi escolar	PRP	5	2.60	1.80	0.89
		Ruvettus pretiosus	Oilfish	OIL	1	2.20	2.20	1.44
	Lampridae	*Lampris guttatus*	Opah	LAG	1	2.40	2.20	1.34
	Lophotidae	*Lophotus capellei*	Crestfish	LOP	5	2.40	2.20	1.34
	Molidae	*Masturus lanceolatus*	Sharptail mola	MRW	5	2.00	1.60	1.17
		Mola mola	Sunfish	MOX	1	2.00	1.60	1.17
		Ranzania laevis	Slender sunfish	RZV	3	2.60	1.60	0.72
	Omosudidae	*Omosudis lowii*	Omosudid (Hammerjaw)	OMW	5	3.00	1.80	0.80
	Scombrolabracidae	*Scombrolabrax heterolepis*	Longfin escolar	SXH	5	2.80	1.60	0.63
	Trachipteridae	*Desmodema polystictum*	Polka-dot ribbonfish	DSM	3	2.80	2.20	1.22
		Zu cristatus	Scalloped ribbonfish	ZUC	5	2.80	2.20	1.22
	Trichiuridae	*Assurger anzac*	Razorback scabbardfish	ASZ	5	2.80	2.20	1.22
		Trachipterus fukuzakii	Tapertail ribbonfish	LHT	5	2.80	2.20	1.22
Tuna-like species	Carangidae	*Elagatis bipinnulata*	Rainbow runner	RRU	1	3.00	2.60	1.60
		Seriola lalandi	Yellowtail amberjack	YTC	5	2.80	1.80	0.82
	Clupeidae	*Opisthonema oglinum*	Atlantic thread herring	THA	1	3.00	2.00	1.00
		Sprattus sprattus	European sprat	SPR	1	3.00	2.00	1.00
	Coryphaenidae	*Coryphaena equiselis*	Pompano dolphinfish	CFW	5	3.00	2.80	1.80
		Coryphaena hippurus	Common dolphinfish	DOL	1	3.00	2.80	1.80

Group	Family	Scientific name	Common name	FAO code	Source	*p*	*s*	*v*
Grupo	**Familia**	**Nombre científico**	**Nombre común**	**Código FAO**	**Fuente**	***p***	***s***	***v***
	Haemulidae	*Pomadasys jubelini*	Sompat grunt	BUR	1	3.00	1.80	0.80
	Scomberesocidae	*Scomberesox saurus*	Atlantic saury	SAU	1	3.00	2.20	1.20
	Scombridae	*Acanthocybium solandri*	Wahoo	WAH	1	2.80	2.80	1.81
		Euthynnus lineatus	Black skipjack	BKJ	7	3.00	2.40	1.40
		Sarda orientalis	Striped bonito	BIP	7	3.00	2.00	1.00
	Sphyraenidae	*Sphyraena barracuda*	Great barracuda	GBA	1	3.00	1.80	0.80

Data sources-Fuentes de datos:

1 IATTC large-scale tuna longline database
2 Zhu & Dai, 2014 China Observer Report to IATTC (SAC-05 INF-C)
3 NIFS 2016 Korea Observer Report to IATTC (SAC-07 INF A(g))
4 Wu, Zhu & Dai, 2015 China Observer Report to IATTC (SAC-06 INF-J)
5 USA 2014 Observer Report to IATTC (SAC-05 INF-G)
6 Venezuela 2016 Observer Report to IATTC (SAC-07 INF A(k))
7 Ecuador 2016 Observer Report to IATTC (SAC-07 INF A(i))

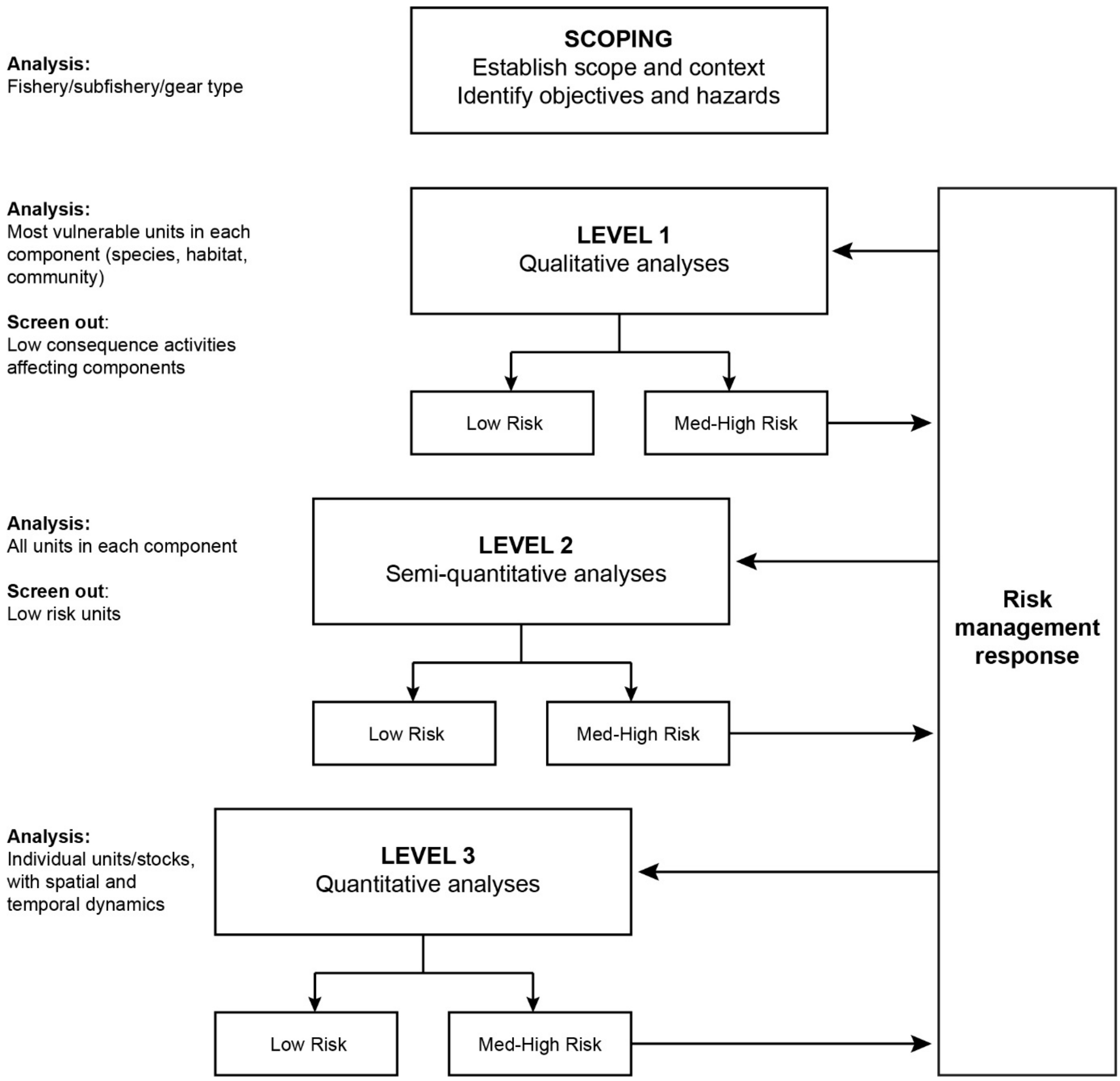

FIGURE 1. Ecological risk assessment framework proposed by Hobday *et al.* (2011), depicting the process of managing ecological risks in fisheries through the use of management responses and increasingly rigorous ecological assessment approaches.

FIGURA 1. Marco de evaluación de riesgos ecológicos propuesto por Hobday *et al.* (2011), ilustrando el proceso de gestionar los riesgos ecológicos en las pesquerías mediante el uso de respuestas de ordenación y enfoques de evaluación ecológica cada vez más rigurosos.

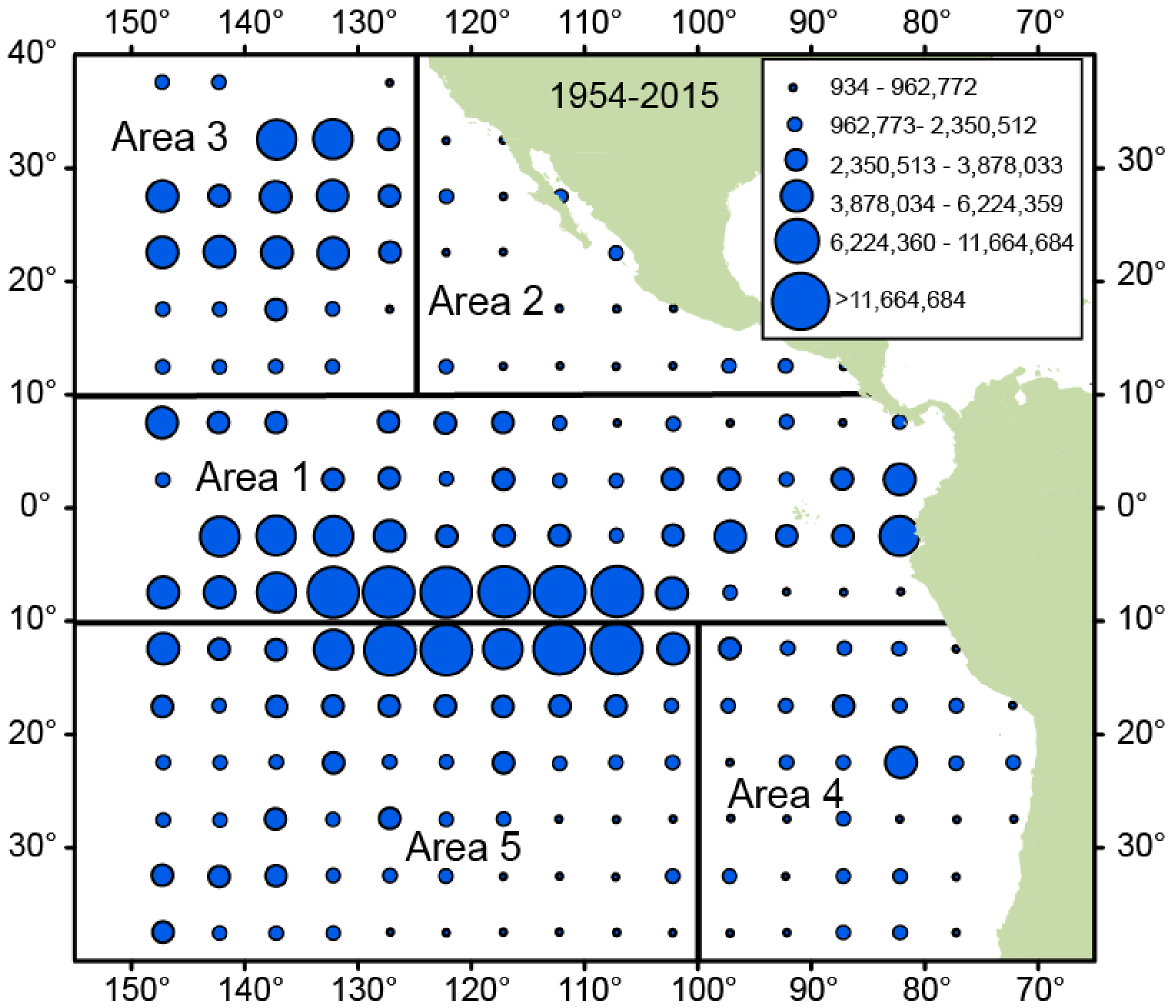

FIGURE 2. Total effort reported to the IATTC, in number of hooks, for the large-scale tuna longline fishery in the eastern Pacific Ocean, 1954-2015. Area stratification to determine the extent of overlap of the fishery with the distribution of impacted species is defined based on historic effort and the analysis areas for swordfish defined by Hinton (2003).

FIGURA 2. Esfuerzo total reportado a la CIAT, en número de anzuelos, de la pesquería atunera palangrera a gran escala en el Océano Pacífico oriental, 1954-2015. Se define la estratificación de las áreas para determinar el grado de superposición de la pesquería y la distribución de las especies afectadas con base en el esfuerzo histórico y las áreas de análisis para el pez espada definidas por Hinton (2003).

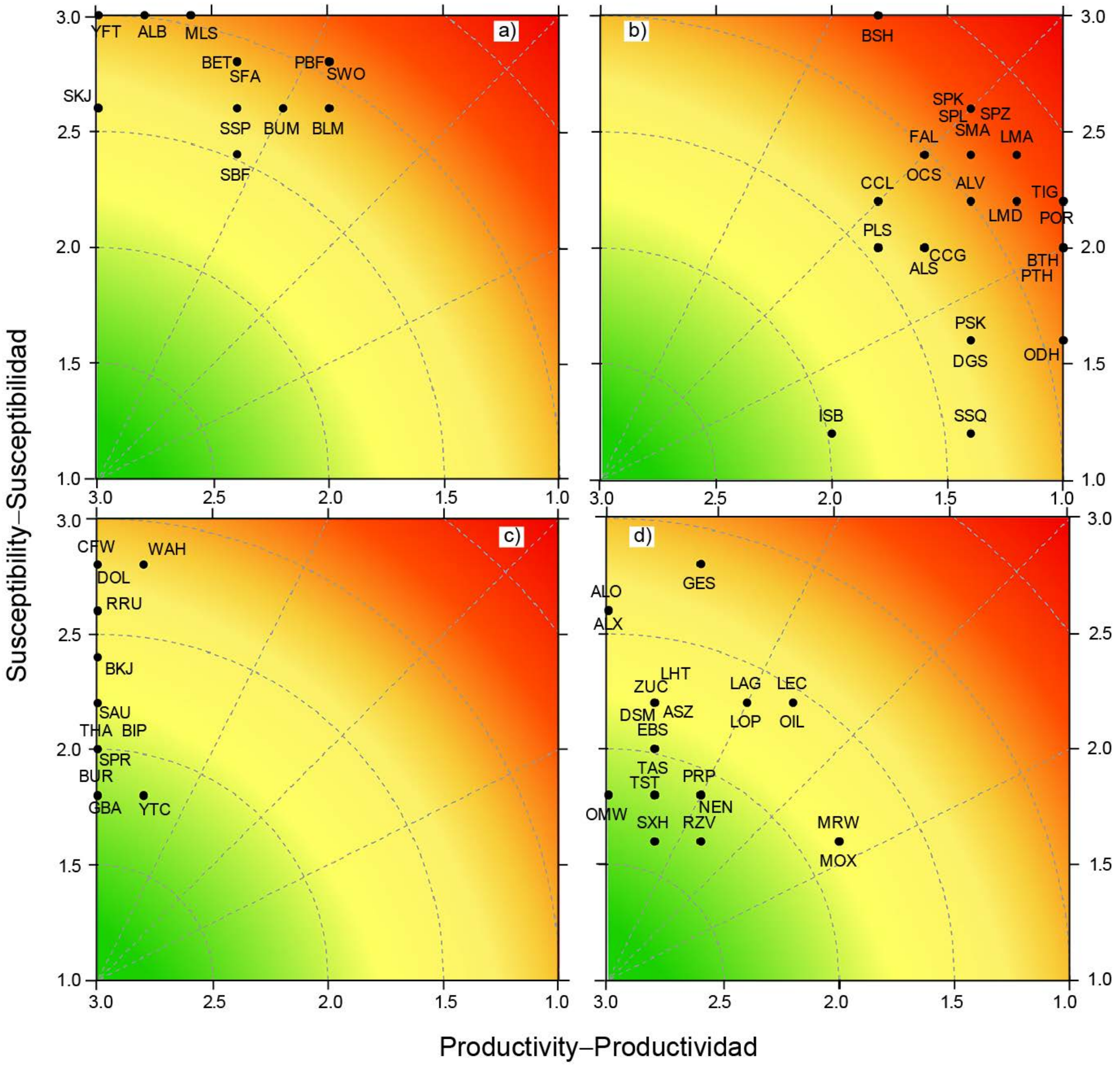

FIGURE 3. Overall productivity and susceptibility scores from the productivity-susceptibility analysis for the 68 species documented to interact with the large-scale tuna longline fishery in the eastern Pacific Ocean: a) principal tuna and billfish species; b) elasmobranchs; c) tuna-like species; and d) mesopelagic fishes caught in shallow sets. Species in the green and red zones are considered to be of lowest and highest vulnerability, respectively. See Table 3 for species codes.

FIGURA 3. Puntuaciones generales de productividad y susceptibilidad del análisis de productividad-susceptibilidad de las 68 especies con interacciones documentadas con la pesquería atunera palangrera a gran escala en el Océano Pacífico oriental: a) especies principales de atunes y peces picudos; b) elasmobranquios; c) especies afines a los atunes; y d) peces mesopelágicos capturados en lances someros. Se considera que las especies en las zonas verde y rojo tienen vulnerabilidades mínimas y máximas, respectivamente. Ver códigos de especies en la Tabla 3.