Ecological risk assessment (ERA) for neritic tunas in the IOTC area of competence

Introduction

Neritic tunas in the Indian Ocean are primarily exploited by coastal fleets operating in the Exclusive Economic Zones (EEZs) of coastal states. Many of these fleets are artisanal and small-scale. Neritic tunas are also taken in industrialised fisheries, including a portion as bycatch by industrial fleets in areas beyond national jurisdiction. As a result, neritic tuna populations and their fisheries are notoriously data-deficient, with the limited data on catch, effort, catch-at-size (age), biology, and population status posing significant challenges for management. In such contexts, Ecological Risk Assessment (ERA) offers an opportunity for systematic examination of population vulnerability to specific gears and fleets, enabling prioritisation for targeted data collection, assessment and research.

Productivity-susceptibility analysis (PSA) constitutes one of the most commonly applied risk assessment approaches. It is a flexible bivariate indicator-based tool that has been adapted to a wide range of data-poor fisheries (Stobutzki et al. 2002; Hobday et al. 2011; Williams et al. 2011). A PSA comprises the construction of indices from attributes indicative of productivity and susceptibility. The framework is essentially based on the logistic model of Schaefer (1954) describing the rate of change of population biomass as a function of carrying capacity, intrinsic rate of population growth and fishery catch (Hobday et al. 2007). An advantage of PSA is that the attributes included can be adapted to local contexts, depending on data availability or relevance to the fisheries to be assessed. For example, while Hobday et al. (2011) apply four attributes to describe susceptibility, or potential exposure, of the population to fishing mortality, Patrick et al. (2010) apply 22 susceptibility attributes in order to consider a wide set of factors relating to socioeconomic drivers of fishing pressure.

PSA is increasingly used as a tool by tuna regional fisheries management organisations (RFMOs) for assessing data-poor fishery components and ecosystem impacts (e.g. bycatch). Within IOTC, applications of PSA have included an analysis of IOTC species using observer data from EU, Soviet Union, Taiwanese and La Reunion purse seine or longline fleets by Murua et al (IOTC-2009-WPEB-20). With the exception of *Thunnus tonggol* and *Scomberomorus guttatus*, neritic tuna species were included in that analysis and found to be of low to moderate risk in terms of their productivity. However, *Euthynnus affinis*, *Auxis rochei* and *A. thazard* were found to be highly susceptible to purse seine gear.

Other PSA applications considered by IOTC working parties have focused on shark species caught in IOTC fisheries (IOTC-2012-WPEB08-31) and megafauna (mammals, turtles, elasmobranchs) that interact with coastal fisheries of the region (IOTC-2012-WPEB08-30).

This study aimed to explore options for PSA in the context of fisheries for the six neritic species considered by IOTC, namely bullet tuna (*Auxis rochei*), frigate tuna (*Auxis thazard*), kawakawa (*Euthynnus affinis*), longtail tuna (*Thunnus tonggol*), narrow-barred Spanish mackerel (*Scomberomorus commerson*) and Indo-Pacific mackerel (*Scomberomorus guttatus*). This version of the paper mainly focuses on the presentation of results stemming from examination of different methods used to estimate productivity, while susceptibility is limited to a proposal of methods. Based on the best options, the study will undertake a PSA for key Indian Ocean neritic tuna species at the 6th Working Party on Neritic Tunas (WPNT06), involving participating experts to validate the approach for assessing productivity and in scoring susceptibility attributes for the selected fisheries.

Methods

Productivity

Method 1

The productivity of neritic tunas was firstly examined using the attributes of Hobday et al. (2011) and Patrick et al. (2010) (hereafter referred to as the 'Hobday' and 'Patrick' approaches, respectively), six of which are common to both approaches (Table 1). Attributes were scored for assessed populations using cut-off points (i.e. thresholds) for low, medium and high productivity (equating to high, medium and low risk, respectively). If sufficient populations are available, context-specific thresholds can be determined statistically. For example, the Patrick approach employed ANOVA and post-hoc tests to identify attribute scoring thresholds for 140 stocks in the USA. Since there are only six neritic species, and it is currently assumed that each consists of a single stock in the Indian Ocean, systematically or statistically defining specific population thresholds is problematic. Nevertheless, the thresholds of Hobday and Patrick are applied to other fisheries (McCully Phillips et al. 2015; Micheli et al. 2014) and were derived from species exhibiting a wide range of life histories and productivity, including neritic tunas.

Information to estimate averages for maximum age and size, size at maturity and the growth coefficient was taken from IOTC population parameter papers for each species (e.g. IOTC-2016-WPNT06-DATA12). Estimation of natural mortality (*M*) followed the methods used to estimate priors for Optimised Catch Only Method (OCOM) stock assessments used by IOTC for data-poor species (e.g. IOTC-2016-WPNT06-17), which provide an average for *M* based on a range of empirical equations. While *r* is also estimated from the same empirical equations in OCOM assessments, this would result in parameters being correlated. Therefore, estimates of the intrinsic rate of population growth (*r*) were derived from the 2016 Catch-MSY assessment results, taking the median *r* across initial depletion levels of the final run. Since this method has not been applied to *A. rochei* and *A. thazard*, *r* estimates were obtained from natural mortality, where $r = 2\,\omega\,M$, and ω (= 0.87) is a scale linking F_{MSY} to M for teleosts (Zhou et al. 2013). For the remaining attributes, information was sourced from www.fishbase.org.

Table 1. Productivity attributes and their scoring thresholds for low, medium and high productivity. Scores are given in brackets, following the Patrick approach. Proposed attribute weights are given.

Productivity attribute	Framework	Low (1)	Medium (2)	High (3)	Weight
Maximum size (cm)	Hobday Patrick	> 300 > 150	40 - 200 60 - 150	< 40 < 60	2
Maximum age (years)	Hobday Patrick	> 25 > 30	10 – 25 10 - 30	< 10 < 10	3
Size at maturity (cm)	Hobday only	> 200	40 - 200	< 40	2
Age at maturity (years)	Hobday Patrick	> 15 > 4	5 – 15 2 - 4	< 5 < 2	3
von Bertalanffy growth coefficient	Patrick only	< 0.15	0.15 - 0.25	> 0.25	3
Natural mortality	Patrick only	< 0.20	0.20 - 0.40	> 0.40	3
Intrinsic rate of population growth	Patrick only	< 0.16	0.16 - 0.5	> 0.5	4
Fecundity*	Hobday Patrick	< 100 $< 10^2$	10 - 20,000 $10^2 - 10^3$	> 20,000 $> 10^4$	2
Reproductive strategy#	Hobday Patrick	Live bearer 0	Demersal layer 1 - 3	Broadcast ≥ 4	2
Trophic level	Hobday Patrick	> 3.25 > 3.5	2.75 - 3.25 2.5 – 3.5	< 2.75 < 2.5	1

*: Fecundity measure differs slightly: Hobday measurement is eggs per year; Patrick measure is number of eggs produced by a female for a given spawning event or period measured at age of first maturity.
#: Reproductive (breeding) strategy in the Patrick approach used the Winemiller index of parental investment in offspring, which influences natural mortality in early life stages. .

Following the Patrick approach, a scheme for weighting attributes in terms of their importance or relevance as indicators of productivity. Weights were based on a scale of 0 (not important, not included in analysis) and 4 (of greatest importance) with 2 given as the default value (Table 1). Age based attributes were considered more informative in terms of productivity than those based on size, while strongly correlated parameters (i.e. natural mortality and the growth coefficient; Charnov 1993) were given equal weights. For each species the weighted productivity score was calculated as: sum(weight × score)/sum(weight). Weights will be validated by experts to WPNT06.

Method 2

The second method used to estimate productivity was based on Kirby et al. (2006), which was applied to species taken in several Indian Ocean fleets (IOTC-2009-WPEB-20) and Atlantic tuna fisheries (Arrizabalaga et al. 2011). This uses a small set of attributes:

p = (reproductive strategy)/3 + (length at maturity/maximum length)

Reproductive strategy categories are equivalent to those used for this attribute in the Hobday approach, with all neritic tunas scoring 1 as broadcast spawners. Consequently, differences between species relate solely to length at maturity relative to maximum size. *P* values were scaled to the maximum of the series. In this method, high *p* values indicate low productivity and high risk (i.e. late maturing relative to maximum size)

Method 3

The final approach considered here for estimating productivity is to select the single most important attribute, namely the intrinsic rate of population growth (*r*). As noted by Musick (1999), *r* is key to resilience, as it incorporates the other life history parameters, and should take precedence in assigning productivity. In line with the approach taken for data-poor stock assessment of neritic species in 2016 (e.g. IOTC-2016-WPNT-6-18), the empirical equation of Then et al. (2014) for estimating natural mortality is adopted, from which *r* is derived as $r = 2\,\omega\,M$ ($\omega = 0.87$). The equation for estimating *M* based on growth parameters is adopted due to the paucity of information on t_{max} for these stocks (Then et al. 2014).

$$M = 4.811K^{0.73}L_{\infty}^{-0.33}$$

where K and L_{∞} are the averages of the von Bertalanffy growth coefficient and asymptotic lengths provided in IOTC population parameter papers for each species.

Susceptibility

As with productivity, susceptibility attributes vary among PSA applications but have tended to be modified from either the schemes of Hobday or Patrick. Since the latter scheme incorporates much of the former, susceptibility attributes were selected from Patrick, with modifications also from McCully Phillips et al. (2015) (Table 2). The scoring criteria adopted were also modified from the available schemes to improve their relevance for neritic tunas in the Indian Ocean. The biomass and fishing mortality rate-based attributes included in Patrick were not adopted here. While assumptions regarding depletion used in data-poor assessments could be applied here, biomass and catch data are unknown and uncertain for *A. rochei* and *A. thazard*.

Susceptibility attributes were assigned preliminary weights according to the method applied for productivity, and will be reviewed by experts at WPNT06.

Neritic tunas are caught in multiple fisheries across their range, within national jurisdictions or by flag state. To consider the cumulative impact of multiple national fisheries at WPNT06, an aggregated susceptibility index (AS) is derived, bounded to a maximum of 3, following Micheli et al. (2014):

$$AS = \min(3, 1 + \sqrt{(FSS_1 - 1)^2 + (FSS_2 - 1)^2 + \cdots + (FSS_{nof} - 1)^2})$$

where *FSS* = fishery-specific susceptibility score, *nof* = number of fisheries scored.

Data quality

Data quality for each attribute scored for a fishery is assessed using the scheme detailed in the Patrick approach, which is then applied to the productivity and susceptibility scores as a weighted average.

Vulnerability

The vulnerability score (*v*) for each fishery is defined as the Euclidean distance of the weighted productivity (*p*) and weighted susceptibility (*s*) scores:

$$v = \sqrt{[(p - x_0)^2} + (s - y_0)^2]$$

where x_0 and y_0 are the (x, y) origin coordinates, respectively. Vulnerability is estimated for individual fisheries, while a combined country vulnerability score is estimated from the aggregate susceptibility index described above.

Table 2 Susceptibility attributes and their scoring thresholds or criteria for low, moderate and high susceptibility adopted from Hobday et al. (2011), Patrick et al. (2010) and McCully Philipps et al. (2015). Proposed attribute weights are given.

Susceptibility attribute	**Low (1)**	**Moderate (2)**	**High (3)**	**Weight**
Areal overlap	< 10% overlap of fishery with stock	10 – 30% overlap of fishery with stock	> 30% overlap of fishery with stock	2
Vertical overlap	Depth fished by gear less than 25% of species depth range	Depth fished by gear 25 - 50% of species depth range	Depth fished by gear >50% of species depth range	2
Seasonal migrations	Seasonal migration decrease overlap with fishery	Seasonal migrations do not substantially affect the overlap	Seasonal migrations increase overlap with the fishery	2
Schooling/aggregation behaviour	Behaviour of fish decrease catchability of gear	Behaviour of fish does not substantially affect catchability of	Behaviour of fish increase catchability of the gear	3
Selectivity	Gear of low selectivity for species	Gear moderately selective for species	Gear highly selective for species	3
Survival after capture and release	Probability of survival > 67%	33% <probability of survival < 67%	Probability of survival < 33%	2
Desirability/value of fishery	Stock is not highly valued or desired by the fishery	Stock is moderately valued or desired by the fishery	Stock is highly valued or desired by the fishery	2
Fishery impact to habitat	Adverse effects absent, minimal or temporary	Adverse effects more than minimal or temporary but are mitigated	Adverse effects more than minimal or temporary and are not mitigated	1
Management strategy	Landings or catches strictly regulated for much of the stock area	Landings or catches partly regulated for the stock area	No management measures that regulate landings or catches for the	3

Results & Discussion

Productivity

Method 1

Estimates of population attributes are provided in Figure 1. Estimates of the intrinsic rate of population growth (*r*) derived from Catch-MSY were similar among species (*S. commerson*, *S. guttatus*, *E. affinis*, *T. tonggol*), while those obtained from Fishbase were higher (*A. rochei*, *A. thazard*). Similarities in *r* from Catch-MSY emerge from prior ranges (0.6 – 1.8) of this parameter being applied equally across species assessments. Given the importance of this parameter to productivity (Musick 1999), alternative approaches to estimation could be considered by WPNT06. Options include estimation of either *M* or *r* using the empirical equations used in OCOM and removal of the other parameter by applying a zero weight. Maximum size, size at maturity and the growth coefficient generally exhibit expected relationships. However, data used for age-based attributes are limited and uncertain for neritic tuna populations, based on few longevity estimates and age at maturity estimation from size at maturity using the inverse of the growth function. Uncertainty in these parameters is carried through to estimation of M, though the inclusion of empirical equations based on growth parameters in addition to t_{max} and t_m will offset this to a degree. Neritic tunas generally occupy similar trophic levels so this attribute is uninformative.

Comparing the (unweighted) productivity scores between the Hobday and Patrick approaches, differences emerge among species rankings (Figure 2). In both approaches, *T. tonggol* (LOT) and *A. thazard* (FRI) are assigned the lowest and highest productivity scores, respectively. By contrast, the rankings of other species shifted between the approaches. The relatively low productivity of *T. tonggol* also stemmed from missing data on fecundity, since the precautionary approach of assigning the lowest productivity scores in such cases was adopted (Hobday et al. 2011). Neritic tunas tended to score as high productivity, with variation in the scores between approaches deriving mainly from the different thresholds for maximum size (Table 1). Similarities in life history traits among neritic tuna also results in tied productivity scores between pairs of species. In the Hobday approach, ties were based on family pairs (*Scomberomorus*, *Auxis*), while tied species pairs were for mixed families in the case of scores from the Patrick approach.

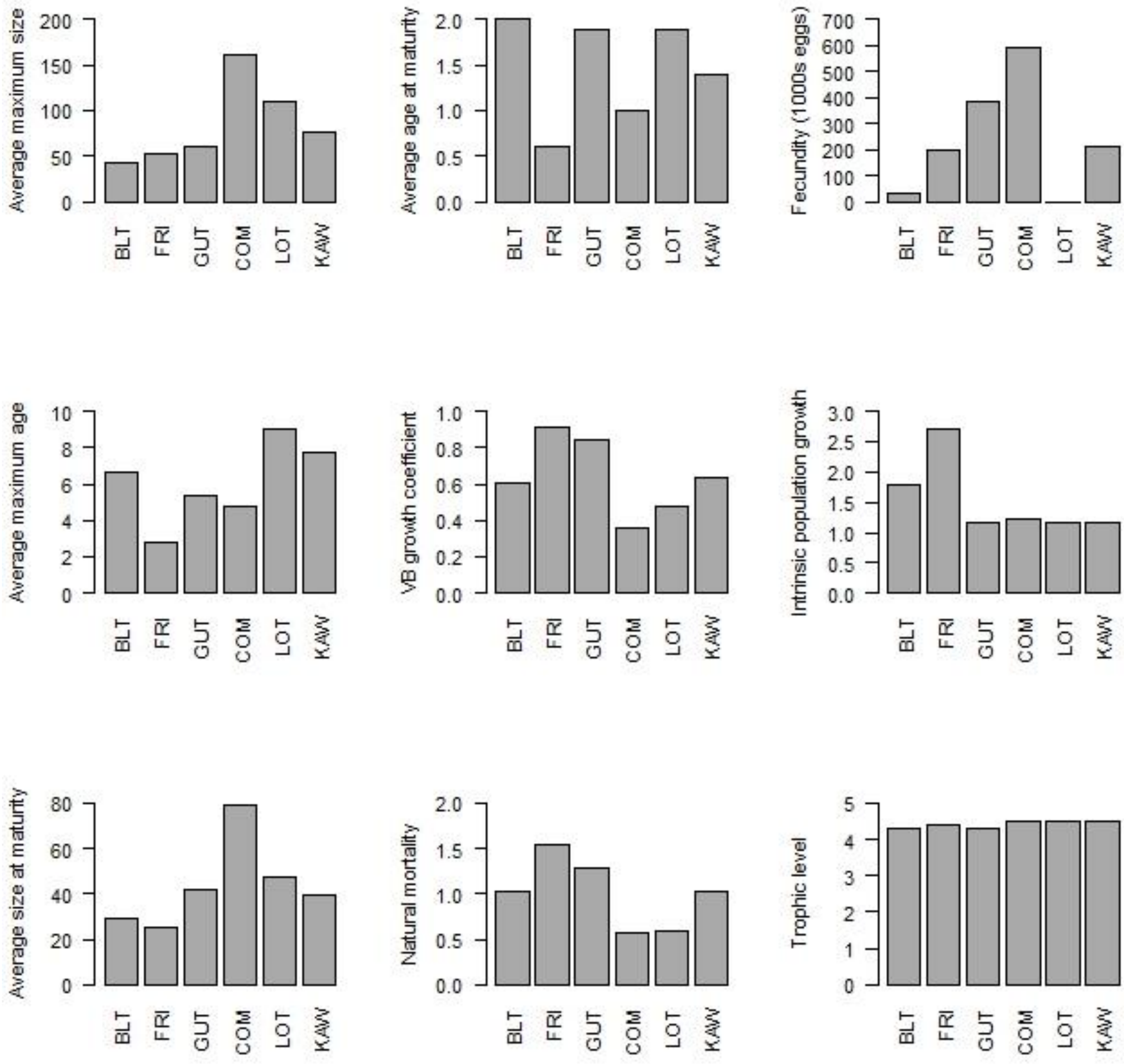

Figure 1 Productivity attributes estimates used in Method 1. See Table 1 for units. Only the minimum of the fecundity range is shown. BLT: *A. rochei*; FRI: *A. thazard*; GUT: *S. guttatus*; COM: *S. commerson*; LOT: *T. tonggol*; KAW: *E. affinis*

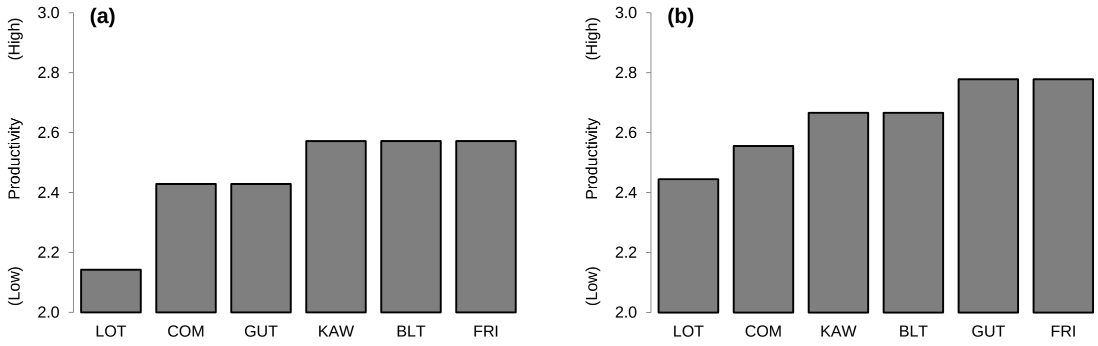

Figure 2 Productivity indices derived from the approaches of (a) Hobday and (b) Patrick. BLT: *A. rochei*; FRI: *A. thazard*; GUT: *S. guttatus*; COM: *S. commerson*; LOT: *T. tonggol*; KAW: *E. affinis*

Methods 2 and 3

Using Method 2, *A. rochei* and *S. guttatus* were assigned scores for low productivity relative to the other species (Figure 3 a). Variation in productivity scores between the other species was relatively minor. Given that *A. rochei* and *S. guttatus* are smaller species generally considered to exhibit fast life histories, at least with respect to *S. commerson* and *T. tonggol*, this method results in implausible estimates of productivity. This index is essentially dependent on size-based attributes, which may be affected by selectivity or unrepresentative sampling in the case of maximum size, or limited information on reproductive biology in the case of size at maturity. For example, only a single estimate of size at maturity was available for *S. guttatus*.

Method 3 produced more plausible estimates of relative productivity given the life history traits of neritic tunas, with levels of productivity increasing from the larger to the smaller species (Figure 3 b). The greater contrast in scores among species than that achieved with Method 2 is also advantageous in assessing relative vulnerability among fisheries. Estimates of growth parameters are relatively numerous for neritic tunas, which lends weight to the selection of Method 3 as a productivity index over that of Method 2.

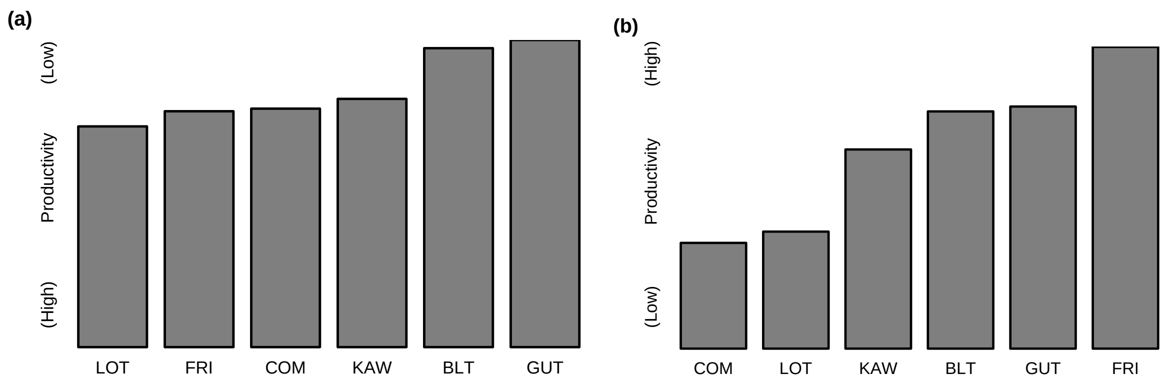

Figure 3 Productivity indices derived from (a) Method 2 and (b) Method 3. Productivity scales on the y-axis operate in opposite directions by method. BLT: *A. rochei*; FRI: *A. thazard*; GUT: *S. guttatus*; COM: *S. commerson*; LOT: *T. tonggol*; KAW: *E. affinis*

Comparison of methods to estimate productivity

Of the methods used to estimate productivity, Method 2 produced the least plausible results and is not considered further. Method 1, which was based on the widely applied frameworks of Hobday and Patrick, resulted in indices that were consistent in ranking the lowest and highest productivity species, but varied in terms of ranking species of intermediate productivity. Many of the attributes included in both these indices were highly uncertain, particularly age-based attributes or attributes derived from empirical equations using age-based parameters. In applying the data quality scores for the full assessment, these age-based attributes are likely to receive poorer quality rankings than those based on size, for which data are rich by comparison in the context of Indian Ocean neritic tunas. Given that the Patrick approach comprises marginally more attributes derived from age parameters (3 versus 2), the alternative may therefore be preferred.

Method 3 is the most parsimonious method and is based entirely on the attributes most widely available for Indian Ocean neritic tunas, namely growth parameters (Then et al. 2014). Consequently, it provides an intuitive index of productivity closely related to maximum size and offers contrast between species.

It is recommended that the full PSA, comprising weighted productivity and susceptibility as well as data quality scores is examined for sensitivity to the three productivity indices derived from Hobday, Patrick and Then et al (2014).

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