SCIENTIFIC COMMITTEE
SEVENTEENTH REGULAR SESSION

Electronic Meeting
11-19 August 2021

Appropriate Limit Reference Points for WCPO Elasmobranchs

WCPFC-SC17-2021/MI-WP-07
(WCPFC-SC16-2020/MI-IP-21)

Shijie Zhou[1], Matthew Dunn[2], Ashely Williams[3]

[1] CSIRO Oceans and Atmosphere, QBP, University of Queensland, 306 Carmody Rd, St Lucia, Brisbane, QLD 4067
[2] National Institute of Water & Atmospheric Research Ltd (NIWA), 301 Evans Bay Parade Hataitai Wellington New Zealand
[3] CSIRO Oceans and Atmosphere, Castray Esplanade, Hobart, TAS, 7001, Australia

Australia's National Science Agency

Appropriate Limit Reference Points for WCPO Elasmobranchs

Shijie Zhou, Matthew Dunn, Ashley Williams

31 August 2020

Citation

Zhou, S., Dunn, M., and Williams, A. (2020). Appropriate Limit Reference Points for WCPO Elasmobranchs. Report to the Western and Central Pacific Fisheries Commission, Brisbane, Australia.

Contents

Figures

Tables

Acknowledgments

We thank Drs John Hampton and James Larcombe for participating in the meeting and discussions. Their constructive comments and edits have improved the quality of the report. We also thank Dr Shelley Clarke and Adam Langley for providing the Silky shark assessment results. Dr Robert Campbell is thanked for guiding the WCPFC processes. During the 16th Regular Session of the Scientific Committee meeting, several members provided helpful comments, including USA, Nauru, Papua New Guinea, Kiribati, and Japan. This project was co-funded by Western and Central Pacific Fisheries Commission and Australian Commonwealth Scientific and Industrial Research Organisation.

Executive summary

Three closely related projects on pelagic elasmobranchs in the Western and Central Pacific Ocean (WCPO) have been conducted in recent years. The first was a thorough review of appropriate limit reference points (LRPs) which was completed in 2014 (Clarke and Hoyle, 2014). This study recommended a tiered framework, similar to that adopted for target species, for defining LRPs for elasmobranch bycatch. Since most elasmobranchs are data-poor stocks, the study strongly suggested that quantitative ecological risk assessments (ERA), also called risk-based approaches, be used for defining LRPs. As ERAs require many life-history parameters (LHPs), the study also identified the collation of information on LHPs as a priority issue, which led to a second project that compiled a comprehensive LHP dataset and produced a report (Clarke *et al.*, 2015). Using this dataset and some additional data from literature, a third project derived risk-based reference points for 15 elasmobranch stocks (Zhou et al. 2019). SC15 recommended that the key conclusions from Zhou *et al*. (2019) be summarized together with any other relevant information.

In this current report, we summarize major sections from Zhou *et al*. (2019). Core elements include: estimating *F*-based reference points; potential methods for estimating fishing mortality; other potential management procedures for WCPFC elasmobranchs; and a review of shark stock-recruitment relationships. Among these four major sections, “estimating *F*-based reference points” is the most relevant to the current project and is the focus in the current study.

We devoted additional effort to explain the rationale of identifying appropriate LRPs. Unlike target reference points for commercial species, LRPs concern the risk to the stock’s sustainability and are set primarily on biological grounds to protect the stock from serious, slowly reversible or irreversible fishing impacts. Therefore, the derivation of LRPs should be based on the same principles for both target and bycatch species. Since the WCPFC has adopted a benchmark $20\%SB_0$ or $20\%SB_{dynamic10,\ unfished}$ as the spawning biomass limit reference point (SB_{lim}) for some tuna target species, similar metrics can be naturally transferred to elasmobranchs. The risk-based approach assumes that the population dynamics follows a Graham-Schaefer production model based on vulnerable biomass where $B_{lim} = 0.5B_{msy} = 0.25B_0$. Corresponding to vulnerable biomass, *F*-based reference points are $F_{lim} = 1.5F_{msy} = 0.75r_{max}$, where r_{max} (or r) is the intrinsic population growth rate. We recommend adopting vulnerable biomass (B_{lim}) and the corresponding F_{lim} as limit reference points for WCPO elasmobranchs because reference points based on vulnerable biomass rather than spawning biomass eases the assessment of data-limited stock, and $0.25B_0$ is close to $0.20SB_0$ for stocks that become vulnerable to fishing gear before maturation. Theoretically, if one of the examined WCPO elasmobranch stocks is depleted to B_{lim}, it can be rebuilt from $0.25B_0$ to B_{msy} in between 5 to 25 years without fishing.

Four methods were used by Zhou *et al*. (2019) for estimating F_{msy} and F_{lim}: (1) empirical relationship between F_{msy} and LHPs based on a meta-analysis of data-rich stocks worldwide; (2) demographic model based on Euler-Lotka equation to derive r; (3) r directly obtained from literature; and (4) spawning potential ratio (SPR) approach. We support the recommendation of using the combined estimate cF_{lim} from Methods 1 to 3 to reduce potential bias caused by a single method where F_{lim} from individual method is computed from F_{msy} as $F_{lim} = 1.5F_{msy}$. Method 4, based on SPR, was not recommended because the level of spawning biomass per recruit varies from stock to stock depending on their productivity, so a constant percentage such as $F_{60\%SPR}$ is not appropriate for all stocks.

The average cF_{lim} for the 15 WCPO stocks was 0.10. These stocks can be roughly grouped into three categories. The two Blue shark stocks can be considered having a high productivity and can sustain an average $cF_{lim} = 0.20$. The medium productive group includes Winghead shark (EUB), Ocean whitetip shark (OCS), Great hammerhead shark (SPK), Whale shark (RHN), and Common thresher shark (ALV). They have a mean $cF_{lim} = 0.12$. Most stocks belong to a lower productive group, including Silky shark (FAL), Scalloped hammerhead shark (SPL), Smooth hammerhead shark (SPZ), Porbeagle shark (POR), Shortfin mako shark (SMA), and Pelagic thresher shark (PTH). This low productive group has a mean $cF_{lim} = 0.06$. In general, fishing mortality should be controlled to lower than 0.25 for high productive stocks, lower than 0.15 for medium productive stocks, and lower than 0.10 for low productive stocks.

There has been some additional information and new developments relevant to defining elasmobranch reference points. A recent study (Cortés and Brooks, 2018) reviewed the ratio between fishing mortality at MSY (F_{msy}) and natural mortality (M) for chondrichthyans. The study concluded that, as a rule of thumb, F_{msy} should not exceed 0.20M for low productivity stocks, 0.50M for stocks of intermediate productivity and 0.80M for the most productive shark stocks when immature individuals are harvested. Because a stock's maximum lifetime reproductive rate (required to quantify productivity) is very difficult to estimate, the authors suggested using $F_{msy} \approx 0.4M$, which is similar to our Method 1, $F_{msy} = 0.41M$.

A new study has developed statistical models to predict SPR_{msy} from life-history parameters (LHPs) for individual stocks (Zhou *et al.*, 2020). We applied this approach to compute SPR_{msy} for elasmobranch stocks in the WCPO. The predicted SPR_{msy} ranged from 0.535 to 0.908 with a mean of 0.721, much higher than the commonly adopted $SPR_{35\%}$ to $SPR_{40\%}$, or even $SPR_{60\%}$ suggested for elasmobranchs in the WCPO. We further converted the estimated SPR_{msy} to F_{msy}. There is a clear correlation between the converted F_{msy} and that from the three risk-based methods and the results are generally comparable. However, estimates of F_{msy} based on SPR_{msy} are more uncertain and require more assumptions than estimates from Methods (1) to (3).

Several recommendations are provided in this report. The most significant one is to adopt $B_{lim} = 0.25B_0$ and corresponding $F_{lim} = 1.5F_{msy}$ as interim LRPs for WCPO elasmobranchs. We do not support the use of a constant percentage of SPR such as $F_{60\%SPR}$ as a reference point for all stocks. Finally, it is important to continue research to provide and improve estimates of life-history parameters and gear selectivity. The estimated reference points should be reviewed and updated when new methods or additional data become available.

1 Introduction

Fishing in the Western and Central Pacific Ocean (WCPO) has direct impacts on 14 major pelagic elasmobranch species. Two distinct stocks have been identified for two of these species: Blue shark and Shortfin mako shark, both with separate North Pacific and South Pacific stocks. Most of the 16 stocks have very limited data, hindering the use of traditional quantitative stock assessments and the development of management advice based on these assessments. Traditional stock assessments have been attempted for only five of the 16 stocks and one of the assessments (South Pacific Blue shark) was inconclusive (Table 1). Developing limit reference points (LRPs) using alternative approaches has been a priority research area for the Commission.

In 2014, Clarke and Hoyle (2014) conducted a thorough review of appropriate LRPs for WCPFC elasmobranchs taking into consideration the WCPFC's LRP framework for target species. They defined three broad types of LRPs: (i) derived from population models; (ii) empirical LRPs directly observed in the field; and (iii) risk-based LRPs based on life-history parameters (LHPs) alone. They recommended a paired (pressure-state) and tiered (based on availability of information) framework similar to that adopted for target species: for those elasmobranchs evaluated using a stock assessment model, a fishing mortality-based LRP of F_{msy} was recommended. In cases where the stock-recruitment relationship is highly uncertain, SPR-based LRP such as $F_{60\%SPR}$ was recommended. When stock assessments are not available, or when the results are not considered robust, risk-based fishing mortality (F_{msy}, F_{lim} and F_{crash}) were recommended.

According to the three types of LRPs, five elasmobranch stocks have been analyzed by type (i): North Pacific Blue shark, South Pacific Blue-shark, North Pacific Shortfin mako, Silky shark, and Ocean whitetip shark (all using Stock Synthesis (SS) software except South Pacific Blue shark which was assessed using Multifan-CL) (Table 1). Risk-based reference points (Type iii) have been applied to three stocks: Bigeye thresher shark (whole Pacific), Porbeagle shark (Southern hemisphere), and Whale shark (Pacific). Additionally, eight stocks have not been assessed by either quantitative stock assessment or ecological risk assessment (ERA, risk-based assessment hereafter) so their biomass or fishing mortality status is unknown. Together, 11 stocks (3 + 8) may have to rely on risk-based reference points.

Risk-based reference points are calculated from various life history parameters (LHPs) (Zhou *et al.*, 2011). Information on LHPs was identified as a priority issue by Clarke and Hoyle (2014). Consequentially, a project funded by WCPFC reviewed over 270 studies worldwide on 16 WCPFC elasmobranch stocks. A comprehensive LHP dataset was compiled by Clarke *et al.* (2015).

Based on this compiled dataset and some new LHPs from literature after Clarke *et al.* (2015), risk-based reference points for all 16 elasmobranch stocks were derived by Zhou *et al.* (2019). In addition, Oceanic whitetip sharks in the WCPO were recently assessed using Stock Synthesis (Tremblay-Boyer *et al.*, 2019). However, due to time constraints, SC15 deferred consideration of these studies on appropriate reference points for elasmobranchs for the WCPFC until SC16. In order to facilitate this process, SC15 recommended that the key conclusions from Zhou *et al*. (2019) be summarized and presented to SC16 together with any other relevant information.

The objective of this report is to summarize existing results and additional new developments in defining reference points for elasmobranchs. The current report is based on existing studies and discusses issues relevant to identifying appropriate LRPs for elasmobranchs. The outcome of this report will facilitate a recommendation by SC16 to WCPFC17 on appropriate LRPs for elasmobranchs in the WCPO.

2 Summary of key conclusions from Zhou *et al*. (2019)

2.1 Overall digest

Zhou *et al*. (2019) described several components related to reference point development. Core sections include: estimating *F*-based reference points; potential methods for estimating fishing mortality; other potential management procedures for WCPFC elasmobranchs; and a review of shark stock-recruitment relationships. We briefly describe each component in Zhou *et al*. (2019) as follows.

(1) A total of four methods were applied to the LHPs compiled in the expert panel report (Clarke *et al*., 2015) to estimate fishing mortality-based reference points (F_{RPs}). Because natural mortality *M* is a key variable in deriving risk-based reference points, *M* was estimated using six *M* estimators as well as adopting *M* values from the literature. Four methods were used to derive F_{RPs}: (i) an empirical relationship between F_{RPs} and LHPs; (ii) demographic analysis; (iii) the intrinsic population growth rate *r* from literature; and (iv) the spawning potential ratio (SPR) approach. Three reference points, F_{msy}, F_{lim}, and F_{crash} were provided.

(2) Potential methods for estimating fishing mortality for data-poor species were reviewed, including formal stock assessment, area-based ERA methods, age-based methods, and length-based methods. The report focused on the area-based methods, as varying versions, tailored for varying data availability, have been developed and have been applied to three elasmobranchs (i.e., Bigeye thresher shark in the Pacific, Porbeagle shark in the Southern hemisphere, and Whale shark in the Pacific). This group of methods can be flexibly modified to suit the available data. This method was recommended for other data-poor WCPFC elasmobranch stocks.

(3) Other potential management procedures for WCPFC elasmobranchs were briefly reviewed. The report discussed three procedures that were potentially promising for WCPFC bycatch: catch-rate approaches, length-based traffic-light approaches, and catch-only methods. The report suggested that before adopting a particular approach, it was essential to check the data inventory against the key assumptions required by the method.

(4) The life history-based approach to estimating a stock recruitment relationship (SRR) for sharks was reviewed, focusing in particular on the approach to derive the steepness parameter for both Beverton-Holt and Ricker's models. The report identified several weaknesses of the approach and recommended further research before applying it to sharks.

Among the four major sections above, the first one "estimating *F*-based reference points" is the most relevant to the current project and we focus on this component.

2.2 Identifying appropriate limit reference points

Limit reference points provide operational definitions of what constitutes unacceptable outcomes, such as unacceptably high fishing mortality, unacceptably depleted fish stocks or unacceptably low profit levels (Sainsbury, 2008). For non-target species such as elasmobranchs, LRPs concern the risk to the stock's sustainability and are set primarily on biological grounds to protect the stock from serious, slowly reversible or irreversible fishing impacts, which include recruitment overfishing and genetic modification. Such a "biological risk" increases as the stock becomes more depleted. Hence, what level of biological risk is considered as "unacceptable" is not only a scientific question but also a social choice. When that limit level is agreed on by stakeholders, this benchmark is typically applied to a wide range of species and stocks in the same jurisdiction (for example 20% of unfished stock biomass, $0.2B_0$, is the limit biomass reference point B_{lim} for commercial species managed by Australia's Commonwealth Government (DAWR, 2018a)). When determining the LRPs, stakeholders also take into account scientific evidence such as stock productivity, possible depensation mechanisms, and ecological interactions among species. If B_{MSY} can be reliably estimated and is above $B_{40\%}$, then $0.5B_{MSY}$ can be an appropriate LRP (Dowling *et al.*, 2008; Sainsbury, 2008). For less productive stocks (such as some elasmobranchs), more conservative biomass LRPs may be adopted—$B_{30\%}$ and associated fishing mortality $F_{30\%}$ being advocated as best practice in some cases (Sainsbury, 2008), noting that these reference points based on per-recruit analysis can vary considerably from stock to stock (see Zhou *et al*. 2020a).

The WCPFC has adopted a benchmark $0.2SB_0$ or $20\%SB_{dynamic10,\ unfished}$ as the biomass limit reference point for some target species (the latter is 20% of the average theoretical level of spawning biomass that would be present during recent 10 years with no fishing) (Clarke and Hoyle, 2014). Zhou *et al*. (2019) discussed and supported adaptation of a similar LRP for non-target species in WCPO on the grounds that the distinction between target and by-catch species is a result of human values and utilisation, rather than one of biology or ecology. LRPs are set to prevent slowly reversible or irreversible biological impacts so there is no biological basis for target and not-target species having different LRPs (Sainsbury 2008). As such, for non-target species, the Convention on the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean (CCMWCPO) adopts "a view to maintaining or restoring populations of such species above levels at which their reproduction may become seriously threatened" (Article 10). This view matches the LRP for target species. Hence, setting aside ecological interaction among species, the biological objective is consistent between target and non-target species.

The LRP $SB_{dynamic10,unfished}$ is the average theoretical level of spawning biomass that would be present during recent 10 years with no fishing. This term of dynamic unfished spawning biomass is used instead of SB_0 (or $SB_{unfished}$) in some WCPFC documents (Clarke and Hoyle, 2014) because it was argued that the underlying assumption of stationarity is less tenable under the emerging understanding of natural ecosystem dynamics and the system-level effects of climate change and other anthropogenic effects (Sainsbury, 2008). SB_0 (or $SB_{dynamic10,unfished}$) cannot be estimated without a time series of data and a quantitative stock assessment. A proxy for SB_0 is needed for non-target elasmobranchs that have no stock assessments. The method in Zhou *et al.* (2019) for deriving risk-based reference points assumed that the population dynamics could be described by a Graham-Schaefer production model where vulnerable biomass $B_{msy} = 0.5B_0$ and $B_{lim} = 0.5B_{msy} = 0.25B_0$. B_{lim} is closer to $0.2SB_{unfished}$ than B_{msy}. Moreover, $0.25B_0$ can be considered as a proxy for $0.2SB_{unfished}$ because the modelled biomass in the Graham-Schaefer production model is the vulnerable biomass instead of spawning biomass. The 15 WCPO elasmobranch stocks have a mean maturation age about 10 years and an intrinsic population growth rate about 0.13 (which can be calculated from F_{msy} in Table 2). Theoretically, on average, a stock can be rebuilt from $0.25B_0$ to B_{msy} in 9 years when fishing stops. Rebuilding time ranges from 4 years for the North Pacific Blue shark (mean maturation age 4.6 yr) to 25 years for Bigeye thresher shark (mean maturation age 11.2 yr). The time frame is within the commonly accepted rebuilding range. For example, in Australia rebuilding time is generally defined as the lesser of the mean generation time (defined as the average age of a reproductively mature animal in an unexploited population) plus 10 years, or three times the mean generation time (Sainsbury, 2008; DAWR, 2018b).

Biomass and biomass-based (or *B*-based) reference points are typically estimated through stock assessment modelling using a range of data. This is unachievable currently for most elasmobranch stocks in the WCPO. Hence, fishing mortality-based (or *F*-based) RPs have been the motivation in risk-based assessments because alternative approaches can be used in addition to stock assessment models.

Corresponding to biomass RPs, *F*-based RPs are calculated as: $F_{msy} = 0.5F_{crash}$, $F_{lim} = 1.5F_{msy} = 0.75F_{crash}$, and $F_{crash} = r_{max}$ (Zhou *et al.*, 2011). Here F_{crash} is the fishing mortality rate that could drive population to extinction if applied for a long term and r_{max} (or r) is the intrinsic population growth rate, a major parameter in the Graham-Schaefer production model. The acronym "F_{msm}" was used by Zhou *et al*. (2019) and Clarke and Hoyle (2014) where “msm” stands for “maximum sustainable mortality” for non-retained bycatch, but it is equivalent to MSY for target species. Hence F_{msm} is identical to F_{msy}.

Among the three RPs presented by Zhou *et al*. (2019) (F_{msy}, F_{lim} and F_{crash}), F_{lim} corresponds to B_{lim} and most likely meets the requirements of Article 10 of the CCMWCPO. This quantity was recommended by Zhou *et al*. (2019) as the appropriate limit reference point for WCPO elasmobranchs. With these contemplations, Zhou *et al*. (2019) and the current study focus on deriving *F*-based LRP F_{lim}.

2.3 Methods for estimating limit reference points F_{lim}

Four methods were used to derive reference points in Zhou *et al*. (2019). All of them rely on life-history parameters. Because F_{lim} is generally computed from F_{msy} as $F_{lim} = 1.5F_{msy}$, both quantities are given in this report.

Method 1: empirical relationship

This is based on the empirical relationship between F_{msy} and life history parameters (Zhou *et al.*, 2012). The relationship varies among taxonomic groups:

(1) $F_{lim1} = 1.5F_{msy1} = 1.31M$ (SD = 0.75) for teleosts

(2) $F_{lim1} = 1.5F_{msy1} = 0.62M$ (SD = 0.14) for chondrichthyans (Eqn 1)

F_{msy1} (and F_{lim1}, where 1 denotes Method 1) may involve two or three levels of uncertainty. If *M* is directly measured from the field (such as tagging) or estimated from population models, F_{msy1} has two levels of uncertainty: measurement error in *M* and process error between F_{msy1} and *M*. If *M* is derived from other LHPs, there will be three levels of uncertainty: measurement error in each life-history parameter (i.e., t_{max}, *K*, L_{inf}, t_0, etc.), process error of the *M*~LHP(s) relationship, and process error between F_{msy1} and the estimated *M*. LHPs come from Clarke *et al.* (2015) and additional literature published after 2015. The measurement error, process error, and variation between studies were assimilated into the calculation through Monte Carlo simulations. The same procedure was applied in other methods below.

Note that the empirical relationships were estimated from a meta-analysis of data-rich stocks worldwide where F_{msy} was estimated from population dynamics models. Therefore, this method implicitly builds in stock-recruitment relationships.

Method 2: demographic model

This method uses the Euler-Lotka equation to derive the intrinsic population growth rate *r*

(Skalski *et al.*, 2008; Cortes, 2016; Pardo *et al.*, 2018):

$$e^{rt_{mat}} - e^{-M}(e^{r})^{t_{mat}-1} - f l_{mat} = 0 \qquad \text{(Eqn 2)}$$

$$F_{lim2} = 1.5F_{msy2} = 0.75r \qquad \text{(Eqn 3)}$$

where t_{mat} is age at first breeding, *f* is constant annual fecundity, l_{mat} the cumulative survival from age 0 to age at maturity. Assuming constant natural mortality leads to $l_{mat} = e^{-Mt_{mat}}$. Annual fecundity *f* is calculated from the reproduction cycle *Rc* and litter size *ls* such that $f = ls/Rc/2$ to account for female pups only. Equation (2) is equivalent to a model for estimating the limits of fishery exploitation (Myers and Mertz, 1998) when it assumes vulnerable age to fishing gear is 1. Age at recruitment is available for 5 out of the 16 WCPFC stocks reported in Clarke *et al*. (2015): BSH-N, SMA-N, SMA-S, LMA, and POR (see acronym in Table 1). All are suggested to be vulnerable to fishing at ages between 0 and 1.

Method 3: *r* from literature

$F_{lim3} = 1.5F_{msy3} = 0.75r$ as in Eqn 3.

Method 4: spawning potential ratio (SPR) approach

SPR is estimated for only a single cohort so does not consider a stock-recruitment relationship. Deriving SPR requires growth parameters (i.e., K, L_{inf}, and t_0), length at maturity L_{mat} or maturity ogive m_o, maximum age t_{max}, length-weight relationship (power function parameters a and b), and fishing gear selectivity curve. Amongst the 16 stocks in the WCPFC region, only four stocks have maturity ogive information (i.e., BSH-N, SMA-N, FAL, and SPL). Furthermore, only one study on gear selectivity for Blue Shark was available (Carvalho and Sippel, 2016) and selectivity and its functional form was assumed for Silky shark and oceanic Whitetip shark. Therefore, this method was applied to these three stocks only.

SPR requires a link between $F_{x\%}$ and F_{msy} and there has been extensive research on the particular percentage (x%) as a proxy for F_{msy}. Zhou *et al*. (2019) provided three reference points: $F_{60\%}$, $F_{40\%}$, and $F_{10\%}$. The authors were unable to investigate what fraction of F_{msy} the SPR-based $F_{60\%}$, $F_{40\%}$ and $F_{10\%}$ may correspond to as this requires a stock-recruitment relationship and may differ from species to species. However, recent development in this area enables SPR_{msy} to be estimated based on LHPs (see below).

2.4 Joint reference points

None of the four methods can be deemed as accurate and the bias and uncertainty may vary from stock to stock due to the quality of available LHPs. Therefore, it is prudent to combine the results from multiple methods to give a more balanced estimation (Brodziak *et al.*, 2009; Kenchington, 2014; Moe, 2015). Depending on the available information, two to four methods were applied to each stock and each method was given the same weight. The combined reference points are cF_{msy} and cF_{lim}. Table 2 lists the summary of cF_{msy} and cF_{lim} from Zhou *et al*. (2019). We excluded cF_{crash} because theoretically fishing mortality at or above this value will drive population to extinction.

2.5 Estimated reference points for individual elasmobranch stock

(1) BSH-N: Blue shark (*Prionace glauca*), North Pacific stock

This stock is relatively "data-rich" amongst the 16 shark stocks because there was sufficient information to apply all four methods. The summary statistics were similar between methods. The mean cF_{msy} was 0.14 (sd 0.07) and the mean cF_{lim}, was 0.23 (sd = 0.11) (**Error! Reference source not found.**). These values were much lower than the results of the full stock assessment using Stock Synthesis that yielded a mean F_{msy} = 0.35 (ranging between 0.26-0.66) (Shark Working Group, 2017). According to the tier approach, SS estimates should be adopted for BSH-N. It is worth noting that a previous assessment of the same stock had a much lower estimate of F_{msy} = 0.22 (Rice *et al.*, 2014). Furthermore, stock assessment for the same species estimated F_{msy} = 0.15 for the North Atlantic Blue shark and F_{msy} between 0.15 and 0.2 for the South Atlantic Blue shark (ICCAT, 2010).

(2) BSH-S: Blue shark (*Prionace glauca*), South Pacific stock

This stock had fewer life-history data available than the same species in the North Pacific. There was a lack of information on the maturity ogive, gear selectivity, the reproductive cycle, and intrinsic rate of increase (r or λ). It was assumed that the reproductive frequency was the same as for the North stocks, and the alternative value of r was borrowed from Atlantic Ocean (Cortés, 2002; Clarke *et al.*, 2015). With the borrowed information, the analysis resulted in mean cF_{msy} = 0.13 (sd = 0.05) and a mean cF_{Lim} = 0.19 (sd = 0.17), both slightly lower than BSH-N stock (**Error! Reference source not found.**).

(3) SMA-N: Shortfin mako shark (*Isurus oxyrinchus*), North Pacific stock

The estimated reference points differed considerably between methods, perhaps due to large variations in life history parameters from different studies. Reproductive cycle was one of the most uncertain parameters used in Method 2. Two studies found *Rc* = 3 yrs (Clarke *et al.*, 2015), but a more recent study indicated a time shorter than 3 yr but exact duration unknown (Semba *et al.*, 2011). Testing alternative *Rc* (2 and 1 yr) while all other parameters were unchanged brought the results from different methods closer each other. Using the database compiled in (Clarke *et al.*, 2015) yielded mean cF_{msy} = 0.04 (sd = 0.03) and a mean cF_{Lim} = 0.06 (sd = 0.04), much lower than for Blue sharks.

(4) SMA-S: Shortfin mako shark (*Isurus oxyrinchus*), South Pacific stock

Life-history parameters were very limited for the South Pacific stock compared to the North Pacific stock. There were no growth parameters (K, L_{inf}, and t_0), fecundity, reproductive cycle, and intrinsic population growth rate available. Maximum age t_{max} had also not been determined for SMA-S but was considered to be greater than 29 yrs for males and greater than 28 yrs for females (Clarke *et al.*, 2015). Using t_{max} = 29 for both sexes and assuming other missing LHPs were the same as SMA-N resulted in a difference between methods (likely overestimating F_{msy1} but underestimation of F_{msy2}). The mean cF_{msy} was 0.03 (sd = 0.04) and a mean cF_{Lim} = 0.05 (sd = 0.05), more uncertain than SMA-N.

(5) LMA: Longfin mako shark (*Isurus paucus*)

Longfin mako shark had very few life-history parameters available, i.e., no other information except length at birth, length at maturity, and litter size. There were also no alternative parameters available from other regions. The limited information was insufficient to apply any method.

(6) FAL: Silky shark (*Carcharhinus falciformis*)

An integrated stock assessment was available for Silky shark (Clarke *et al.*, 2018) and F_{msy} was estimated to be 0.031 (S. Clarke, personal communication). A previous stock assessment yielded a much higher F_{msy} of 0.077 (Rice and Harley, 2012).

Early studies reported much smaller t_{max} than the same species in other regions. Instead of using compiled LHPs from the Cairns workshop, Zhou *et al*. (2019) used the newly estimated life history parameters, including t_{max} (28 yr), t_{mat}, L_{inf}, K, t_0, and L_{mat} from Grant *et al.* (2018). These new values and a knife-edge selectivity at 64 cm total length led to reasonably similar reference points from the four methods. The mean cF_{msy} from Methods 1, 2, and 3 was 0.06 (sd = 0.03) and a mean cF_{Lim} = 0.09 (sd = 0.05).

(7) OCS: Oceanic whitetip shark (*Carcharhinus longimanus*)

The most recent stock assessment produced F_{msy} = 0.06 for Ocean whitetip shark (Tremblay-Boyer *et al.*, 2019). This is slightly smaller than the risk-based F_{msy}. The greater longevity estimate from the two available studies (11 yrs and 36 yrs) was used t_{max} = 36. The mean cF_{msy} was 0.08 (sd = 0.05) and cF_{lim} was 0.12 (sd = 0.07).

(8) BTH: Bigeye thresher shark (*Alopias superciliosus*)

The estimated intrinsic rate of increase λ by demographic analysis from the literature was 0.996 (ranging between 0.0978 and 1.014)(Cortés, 2002; Clarke *et al.*, 2015). This suggests that the Bigeye thresher shark in the Pacific would suffer a negative population growth rate even with no fishing.

Recently, a detailed risk-based assessment was conducted for the Bigeye thresher shark (Fu *et al.*, 2018), which borrowed the longevity of 22 yrs for females in the Atlantic Ocean. Using the same value (t_{max} = 22 yrs) for both males and females, and all other parameters from the Clarke *et al*. (2015) report), the estimated mean cF_{msy} was 0.02 (sd = 0.04) and cF_{lim} was 0.04 (sd = 0.06).

(9) PTH: Pelagic thresher shark (*Alopias pelagicus*)

The estimated reference points varied between the three methods, possibly due to uncertain t_{max} and growth parameters. Based on the compiled LHPs, the estimated mean cF_{msy} was 0.04 (sd = 0.03) and cF_{lim} was 0.06 (sd = 0.04).

(10) ALV: Common thresher shark (*Alopias vulpinus*)

Two empirical M estimators, one based on t_{max} and the other one based on k and L_{inf} led to very different natural mortality estimates. Method 1, using the average M, resulted in moderately similar reference points between the three methods. The combined mean cF_{msy} was 0.07 (sd = 0.03) and cF_{lim} was 0.10 (sd = 0.05).

(11) POR: Porbeagle shark (*Lamna nasus*)

Only two methods were applied to Porbeagle shark, as there was no estimated intrinsic population growth rate in literature. The estimated M was more similar between the seven methods than many other species. Recently, Hoyle *et al.* (2017b) conducted a risk-based stock-assessment for the southern hemisphere porbeagle shark and used updated LHPs since the Clarke *et al*. (2015) report. Using the updated LHPs the estimated mean cF_{msy} was 0.04 (sd = 0.03) and cF_{lim} was 0.06 (sd = 0.04).

(12) SPZ: Smooth hammerhead shark (*Sphyrna zygaena*)

Only two methods were applied to the Smooth hammerhead shark, as there was no estimated intrinsic population growth rate in literature. Moreover, there was also no age at maturity t_m, longevity t_{max}, reproductive cycle *Rc*, and natural mortality rate M for this stock in the Pacific. To apply Method 2, alternative parameters t_m and t_{max} were borrowed from Atlantic Ocean and *Rc* was assumed to be 1 yr. These treatments led to a mean cF_{msy} of 0.05 (sd = 0.04) and cF_{lim} of 0.07 (sd = 0.06).

(13) SPL: Scalloped hammerhead shark (*Sphyrna lewini*)

The t_{max} differed significantly between males (21 yrs) and females (35 yrs) and the larger value was used for both sexes. The estimated reference points from the three methods were relatively comparable with other species. The mean cF_{msy} was 0.05 (sd = 0.02) and cF_{lim} was 0.07 (sd = 0.03).

(14) SPK: Great hammerhead shark (*Sphyrna mokarran*)

There was no estimated intrinsic population growth rate available for the Great hammerhead, so only Methods 1 and 2 were used to derive reference points. The mean cF_{msy} was 0.07 (sd = 0.03) and cF_{lim} was 0.11 (sd = 0.05).

(15) EUB: Winghead shark (*Eusphyra blochii*)

There was no estimated natural mortality or intrinsic population growth rate in the literature so only Methods 1 and 2 were used. The estimated *M* based on t_{max} was again higher than the estimate based on growth parameters, indicating possibly underestimated t_{max} (21 yr from vertebral growth band pairs). The mean cF_{msy} was 0.09 (sd = 0.04) and cF_{lim} was 0.14 (sd = 0.06).

(16) RHN: Whale shark (*Rhincodon typus*)

There was no estimated intrinsic population growth rate, natural mortality, or reproductive cycle in the literature. Longevity, maximum length, and age at maturity were observed values or estimated from small samples. The estimated *M* based on growth parameters was very small compared to *M* based on other estimators (mean 0.03 vs 0.08), but the average of 0.08 from all *M* estimators was smaller than for other species. The estimated intrinsic population growth rate from Method 2 (Euler-Lotka equation) was 0.22, which is similar to the recent demographic analysis (Neubauer *et al.*, 2018). The mean cF_{msy} was 0.07 (sd = 0.04) and cF_{lim} was 0.11 (sd = 0.06).

The average cF_{lim} for the 15 stocks was 0.10 (Table 2). These stocks can be roughly grouped into three categories. The two Blue shark stocks can be considered having a high productivity. They can sustain an average cF_{lim} = 0.20. The medium productive group includes Winghead shark (EUB), Ocean whitetip shark (OCS), Great hammerhead shark (SPK), Whale shark (RHN), and Common thresher shark (ALV). They have a mean cF_{lim} = 0.12. Most stocks belong to a lower productive group, including Silky shark (FAL), Scalloped hammerhead shark (SPL), Smooth hammerhead shark (SPZ), Porbeagle shark (POR), Shortfin mako shark (SMA), and Pelagic thresher shark (PTH). This low productive group has a mean cF_{lim} = 0.06. In general, fishing mortality should be controlled to lower than 0.25 for high productive stocks, lower than 0.15 for medium productive stocks, and lower than 0.10 for low productive stocks. Because of high uncertainties and potential biases in the LHPs, the methods used to estimate LRPs, and the estimated LRPs *per se*, lower limits than these approximations may be adopted for the management of the elasmobranchs.

3 Additional information and new development

3.1 Stock status and reference points for sharks using data-limited methods and life history

In a paper published in Fish and Fisheries, Cortés and Brooks (2018) reviewed the ratio between fishing mortality at MSY (F_{msy}) and natural mortality (M) for chondrichthyans, from published studies and shark stock assessments. They compared conclusions on overfishing status from the stock assessments to those derived with F_{msy} proxies and found very good agreement. They also conducted a simulation study across representative LHPs and different fishery selectivity patterns to explore the resulting range of F_{msy} to M ratios. They concluded that, as a rule of thumb, F_{msy} should not exceed 0.20M for low productivity stocks, 0.50M for stocks of intermediate productivity and 0.80M for the most productive shark stocks when immature individuals are harvested, which is the norm in the vast majority of cases examined.

To quantify productivity of a population, they used the maximum lifetime reproductive rate $\hat{\alpha}$ (number of spawners produced by each spawner over its entire lifetime) at low stock density (Myers *et al.*, 1997, 1999; Brooks *et al.*, 2010). They grouped results for the F_{msy}/M scalar into three productivity categories: "low" corresponds to $\hat{\alpha}$ = [1.50–2.67]; "medium" corresponds to $\hat{\alpha}$ = [2.671–6.00]; "high" corresponds to $\hat{\alpha}$ = [6.01–13.00].

It has been shown that $\hat{\alpha}$ can be calculated as the product of unexploited spawners per recruit ($SPR_{F=0}$) and the slope at the origin of a stock-recruit curve (Myers *et al.*, 1997; Brooks and Powers, 2007). However, not all stocks have the required data to allow establishing stock-recruit curve and calculation of $\hat{\alpha}$. More importantly, if there are sufficient data to allow calculating $\hat{\alpha}$, then the straightforward reference point SPR_{msy} (SPR at MSY) can be obtained by $SPR_{MSY} = \sqrt{\frac{1-h}{h}} = \frac{1}{\sqrt{\hat{\alpha}}}$ (Brooks *et al.*, 2010; Mangel *et al.*, 2013). Hence, they suggested that for many shark stocks, the F_{msy}/M ratio should not exceed ≈ 0.4, which is similar to our Method 1, F_{msy1} = 0.41 M. Note that this reference point may be too conservative for high productive stocks but risky for low productive stocks such as Whale shark.

3.2 Identifying spawner biomass per-recruit reference points from life-history parameters

Zhou *et al*. (2019) found that it is difficult to define a specific x% for the SPR-based reference points. There has been extensive research on the particular x% as proxy for F_{msy}. For example, in a review of biological reference points for precautionary approaches, Gabriel and Mace (1999) recommended that fishing mortality rates in the range $F_{30\%}$ to $F_{40\%}$ be used as general default proxies for F_{msy}. For the elasmobranchs in the WCPO, Clarke and Hoyle (2014) suggested that in cases where the stock-recruitment relationship is highly uncertain, $F_{60\%SPR}$ could be considered as SPR-based LRP. Clearly, an arbitrary chosen $F_{x\%}$ for all stocks regardless their productivity is problematic.

Recently, Zhou *et al.* (2020) used records from stock assessments in the RAM Legacy Database (RAMLD) to confirm that SPR_{msy} is a declining function of stock productivity quantified by F_{msy}, i.e., SPR_{msy} is not a constant value (such as 30%, 40%, or 60%) but varies from stock to stock like F_{msy}. They then developed statistical models to predict SPR_{msy} from LHPs, including maximum lifespan, age- and length-at maturation, growth parameters, natural mortality, and taxonomic Class, as well as gear selectivity.

Using the estimated measurement error and parameter for each LHP in Zhou *et al.* (2020), we computed SPR_{msy} for elasmobranch stocks in the WCPO (Table 3). We cannot apply the method to Longfin mako shark (LMA) because this stock had little information on its LHPs. Selectivity is unknown for most stocks, which is also the case in the RAMLD used to develop the SPR_{msy} models. To be consistent with the SPR_{msy} model in Zhou *et al.* (2020), we also assumed that fish become vulnerable at first maturation, i.e., $t_v \geq t_{mat}$., where t_v is the vulnerable age. Note that if fishing mortality occurs before maturation, which is likely for many sharks (Cortés and Brooks, 2018), in both RAMLD and here in WCPO, our predicted SPR_{msy} would be less biased.

The predicted SPR_{msy} ranges from 0.535 to 0.908 with a mean of 0.721 (Table 3). These values are higher than the commonly adopted $SPR_{35\%}$ to $SPR_{40\%}$. For most stocks they are also greater than $SPR_{60\%}$ suggested for elasmobranchs in the WCPO (Clarke and Hoyle, 2014).

We further converted the estimated SPR_{msy} in Table 3 to F_{msy}. The conversion requires all the LHPs used to calculate spawning biomass per-recruit (including growth function, age or length at maturation, maximum age, natural mortality, length-weight relationship, and selectivity), and an optimization function to minimize the difference between the estimated SPR_{msy} and a fishing mortality rate (i.e. F_{msy}) to achieve a SPR level at SPR_{msy}.

The distributions of F_{msy} converted from SPR_{msy} are skewed toward small values (see the difference between the mean and median in Table 4) and the uncertainty is substantial (mean cv = 1.33). To compare with previous analyses, we used median F_{msy} (

Figure 1). There is a clear correlation (r = 0.56) between the two sets of results, one from three risk-based methods and the current SPR_{msy} converted F_{msy}. If the two data-poor stocks (EUB and RHN) are excluded from the comparison, the Pearson correlation coefficient increases to r = 0.73.

Similar to SPR_{msy}, there is a SPR-based LRP – SPR_{lim} – that corresponds to B_{lim} and F_{lim}. SPR_{lim} can be computed from F_{lim} together with LHPs and selectivity. However, unlike a constant relationship between F_{lim} and F_{msy}, the ratio between SPR_{lim} and SPR_{msy} is not constant and is often greater than 0.5 (e.g., if SPR_{msy} = 60%, typically SPR_{lim} > 30%).

We also included four stocks that have been assessed by Stock Synthesis: BSH-N, SMA-N, OCS, and FAL. For BSH-N the full stock assessment yields F_{msy} = 0.35 (Shark Working Group, 2017), and F_{msy} = 0.22 in an earlier assessment (Rice *et al.*, 2014), which are greater than cF_{msy} = 0.14 and SPR_{msy} converted F_{msy} = 0.13 (Table 2 and Table 4). This stock has a mean M = 0.23 (sd=0.08). Even if it is considered as a highly productive stock, according to Cortés and Brooks (2018), F_{msy} should not exceed 0.8*M = 0.184. The full stock assessment reported F_{msy} = 1-SPR_{msy} = 0.26 for the Short-fin mako shark (ISC Shark Working Group, 2018). This equation appears to be ad hoc, but its SPR_{msy} = 1 - 0.26 = 0.74 is identical to our predicted mean SPR_{msy} (Table 3). Hence, the converted F_{msy} should also be the same as our F_{msy} (mean 0.061, Table 4) rather than 0.26. For the third stock, the full stock assessment resulted in F_{msy} = 0.06 for the Ocean whitetip shark (Tremblay-Boyer *et al.*, 2019), which is smaller than cF_{msy} = 0.08 and SPR_{msy} converted F_{msy} = 0.09 (

Figure 1). The most recent stock assessment on Silky shark estimated F_{msy} = 0.031 (Clarke *et al.*, 2018), which is only 40% of the value (F_{msy} = 0.077) estimated in an earlier integrated stock assessment (Rice and Harley, 2012). However, the earlier value may have been over-estimated.

3.3 Estimating intrinsic population growth *r* from life-history traits

A lack of time series of fishery and population data has prevented stock assessments for many elasmobranch stocks. Using demographic analysis to estimate the intrinsic rate of population increase r and the deriving F-based reference points based on r has been the most widely accepted approach. An alternative approach is currently been investigated (Zhou *et al.*, 2020b). This new approach uses r estimates derived from the Schaefer surplus production model for fish and invertebrate stocks worldwide to develop empirical relationships between r and various LHPs based on Bayesian hierarchical error-in-variable models (BHEIVMs) that incorporate uncertainty in LHPs themselves. Among the various models tested, it is found that the maximum age (t_{max}) has the most significant effect on r estimates, followed by natural mortality rate (M). Other LHPs add minor improvement to the relationship when t_{max} and M are included in the model. The best models, selected based on the deviation information criteria (DIC) and Bayesian p-value, are $r = 2.663/t_{max}$ and $r = 0.661M$ for elasmobranchs. If these relationships are adopted for stocks in the WCPO, the estimated reference points F_{msy} and F_{lim} for many stocks in Zhou *et al*. (2019) and Table 2 would be slightly adjusted downward. However, since that study has not been formally peer-reviewed and published, it is not recommended to be adopted at this stage.

4 Discussion and recommendations

The key objective in Zhou *et al*. (2019) was to recalculate the risk-based limit reference points using the updated life history information produced by the Shark Life History Expert Panel (Clarke *et al.*, 2015). Identifying LRPs for non-target species from management objectives point of view was discussed. In this report we further elucidate the logic of determining appropriate LRPs from the WCPFC adopted benchmark for target species, to acceptable level of biological risk, the relationship between *B*-based and *F*-based RPs, and the choice of F_{lim} as the recommended LRP for elasmobranchs.

Data availability varies among the 16 major WCPO elasmobranchs. Accordingly, full stock assessments have been conducted only for 5 stocks, and risk-based assessments have been applied to three stocks. We support the earlier recommendation of a tiered framework. For those elasmobranchs evaluated using a full stock assessment model, reference points and stock status estimated in the same stock assessment should be adopted. In addition, estimating reference points and fishing mortality simultaneously in a population dynamics model avoids the potential inconsistency of demographic composition used to estimate F_{cur} and F_{BPR} when they are derived separately. However, adopting stock assessments as a Tier one approach does not mean the results are accurate. Although quantitative stock assessments using a range of information are regarded as the highest standard, the estimated parameters can contain large uncertainties. For example, the Stock Synthesis assessments are heavily driven by CPUE data, which is often an unreliable index of abundance and potentially misleading, particularly for elasmobranchs. The large difference of the estimated F_{msy} between two stock assessments for both North Pacific Blue shark and Silky shark raises the concern of the reliability of integrated assessments.

Multiple methods have been used to develop *F*-based reference points for WCPO elasmobranch stocks in Zhou *et al*. (2019) and additional methods are explored in the current report. Method 1, based on empirical relationships, was applied to all 15 stocks (except Longfin mako shark). Not all stocks have available LHPs required by Method 2 (demographic analysis). Borrowing some LHPs from other regions for some stocks and making assumptions about the reproductive cycles for several stocks made it possible to apply Method 2 to all 15 stocks. The mean RPs across the 15 stocks are nearly identical between methods 1 and 2: 0.06 vs 0.07 for F_{msy}, and 0.10 vs 0.10 for F_{lim}, respectively. However, the estimated RP values for individual stock can be different between the two methods and their correlation is low. The empirical method is less likely to yield extreme estimates than the Euler-Lotka equation.

Method 3, based on intrinsic population growth rate from the literature, was applied to 10 stocks. The results from this method are similar to Method 2. The correlation between Methods 2 and 3 (corr = 0.85) is much higher than the correlation between Methods 1 and 2 (corr = 0.43) or between Methods 1 and 3 (corr = 0.67). This is likely because *r* from literature is often also derived from demographic analysis.

It is difficult to conclude which method is the best across all species. Besides, the effect of alternative methods, available LHPs and their quality, have a marked impact on the quality of the estimated reference points. The combined reference points cF_{msy} and cF_{lim} from multiple methods can reduce potential bias introduced by using a single method and are deemed more reliable for most stocks (Brodziak *et al.*, 2009; Moe, 2015). Therefore, the joint RPs should be adopted for managing WCPO data-poor elasmobranchs.

There are a range of knowledge and data gaps in defining LRPs for WCPO elasmobranchs. For the risk-based approach alone, the first drawback is the lack of LHPs required by alternative methods. Reproductive cycle and annual fecundity (litter size) are unknown for several stocks. Gear selectivity is available for only three stocks. Longfin mako shark has no life-history parameters available except length at birth, length at maturity, and litter size. For those stocks that have LHPs available in the literature, uncertainty around the

LHPs can be considerable. Zhou *et al*. (2019) discussed these issues and their effect on the estimated reference points. In particular, maximum age may have been underestimated for most stocks for the following reasons: (i) t_{max} is either observed or estimated from a population that has been fished for many years; (ii) old fish are rare and difficult to capture; (iii) the common method of ageing sharks and rays can substantially underestimate true age (Francis *et al.*, 2007; Hamady *et al.*, 2014; Harry, 2018). Uncertain LHPs can lead to inaccurate or biased reference points.

Selectivity is a crucial variable for all methods. To be valid, for methods based on empirical relationships between F_{msy} and LHPs (Method 1) and SPR_{msy} and LHPs (new method), selectivity should not be markedly different between the fisheries used to build the models and the sub-fisheries in the WCPO that impact on the elasmobranch stocks. Selectivity should be estimated for all elasmobranchs in the WCPFC jurisdiction. If selectivity cannot be modelled, a knife-edge size (or age) of entry to the fishery may be determined by length samples of the observed catch.

Zhou *et al*. (2019) did not recommend SPR-based reference points because at that time there was no method for estimating stock-specific SPR_{msy} so a generic constant of 40% or 60% SPR was adopted for all stocks. The new development has enabled estimation of stock-specific SPR_{msy} from LHPs. The new study affirms that SPR_{msy} indeed varies among stocks and even $F_{60\%SPR}$ can be too risky for most WCPO elasmobranchs. Although SPR-based reference points can now be estimated for each stock, this approach requires more information and assumptions, and hence is more prone to bias than the other three methods. It is recommended not to use SPR-based RPs but to adopt the combined reference points from the other three methods. It is worth pointing out again that although SPR refers to spawning biomass, this biomass is not the biomass of the population but a relative value, in terms of "per recruit". Any arbitrarily number, such as 1 or 1000 fish, can be used as the initial population size to derive SPR. Applying a fixed SPR-based reference point with a constant percentage such as $F_{40\%SPR}$ to all stocks is inappropriate because it does not take stock productivity into account.

Until now, limit reference points have not been agreed on for pelagic sharks in the Pacific Ocean. In the full stock assessment of the four elasmobranch stocks, reference points are reported in relation to MSY. Achieving MSY is the objective for managing target species stipulated in the Convention on the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean (CCMWCPO). In this project, the WCPFC specifically seeks appropriate limit reference points for non-target WCPO elasmobranchs. Non-target species in the WCPFC do not have a target reference point. To ensure management constancy between target and non-target stocks, F_{lim}, ideally calculated from multiple methods as cF_{lim}, is recommended as the *F*-based limit reference point for pelagic elasmobranchs. This reference point corresponds to B_{lim} that is 25% of vulnerable virgin biomass B_0 and is closer to $20\%SB_{unfished}$. If the stock is depleted to B_{lim}, rebuilding to B_{msy} could take about 9 years on average for the 15 stocks we examined in the report when there is no fishing (ranges from 4 year for the North Pacific Blue shark to 25 years for Bigeye thresher shark).

During the 16th Regular Session of the Scientific Committee meeting in August 2020, some members suggested that MSY-based reference points should be considered as candidate reference points *a priori* to be consistent with the Convention text "*ensure that such measures are based on the best scientific evidence available and are designed to maintain or restore stocks at levels capable of producing maximum sustainable yield*". The LRP recommended in this report also caused concern that, with stocks below this level, there are risks of increasing variability in recruitment and reductions in average fish size (and value) resulting in undesirable economic and social impacts. As stated in section 2.2 (*Identifying appropriate limit reference points*), LRPs concern the risk to the stock's sustainability rather than fishery's profitability and are set primarily on biological grounds rather than on economic and social grounds. For protected and bycatch species that have no commercial value, the ideal reference point is zero fishing mortality, if ecological interactions (e.g. predation on target species and maintenance of ecosystem structure) are not urgent factors in management decisions (Garcia *et al.*, 2012). However, setting a higher biomass LRP or a lower fishing mortality LRP for bycatch species may have undesirable consequences on allowable catch level of target species when the bycatch species becomes a choke species. Balancing the risk and benefit between target and non-target species is not only a science question but a social choice. The Commission should provide clear guidelines on management objectives including acceptable levels for the ecological effects of fishing. Members are encouraged to discuss recommended LRPs in this report and reach an agreement on the acceptable LRP level.

There was a suggestion in the SC16 that an agreement is needed on the metrics used to describe the stock status. It was recommended using $SB/SB_{F=0}$ or SB/SB_0 as metrics to describe stock depletion resulting from data rich assessments. We agree that reference points based on spawning biomass is a sensible choice and can be used for stocks assessed using age-structured models. However, for stocks with limited data, the concept based on biomass dynamics models (as used in this report) is preferred. Here, the modelled biomass is vulnerable biomass rather than spawning biomass. Simply using vulnerable biomass eases the estimation of total biomass and fishing mortality rate because any fish captured in fisheries is vulnerable to the fishing gear but that fish may be or may not be mature. This advantage is particularly helpful for data-limited stocks that are assessed by risk-based methods. Vulnerable biomass is greater than spawning biomass when fishing causes mortality to immature fish, which is often the case for WCPO elasmobranchs. As such, if the LRP is defined as $0.2SB_{F=0}$, $B/B_{F=0}$ should be greater than 0.2. Our recommended $B_{lim} = 0.25B_0$ manifests this point.

Not to include F_{crash} as a potential LRP was a concern to some member countries. We iterate that F_{crash} is not a sensible reference point for management of any marine species, unless the objective is to eradicate that species (e.g., invasive species in some freshwater systems). To prevent severely depleting the population, fishing mortality must be lower than F_{crash}, e.g., $F_{lim} = 0.75F_{crash}$.

Some members suggested that when useful data on the catch are available, the use of empirical reference points such as CPUE (e.g. x% CPUE from some reference period) would be useful to consider as an interim LRP. Empirical reference points were discussed in Zhou *et al*. (2019) but that section was not included in the current report. We envision that empirical reference points could be potentially defined for some stocks with sufficient and reliable CPUE data and could be investigated on the stock by stock basis. The drawback of empirical reference points is their inability to link to stock status, either in terms of biomass or fishing mortality. The stock status in the reference period is unknown; stakeholders may have difficulties to agree on what period should be defined as reference period and what level of x% should be adopted, let alone the inaccuracy of CPUE time series and challenges in estimating increases in fishing power. Nevertheless, it would be useful for an analysis to be undertaken investigating the possibility of CPUE or other empirical reference points for elasmobranchs.

The analysis and discussion so far deal with individual stock independently without taking ecological interactions into account. Because most elasmobranchs are typically high trophic level predators, the abundances of their prey species may have declined due to fishing, which may have already led to a proportional decline of these elasmobranchs from their unfished population size. In addition to this bottom-up effect, any additional fishing mortality on predators will further reduce their biomass. Hence, accepting $F = F_{lim}$ will eventually drive population lower than true B_{lim} for predatory sharks when there was no fishing in the WCPO ecosystem. If the stakeholders regard ecological sustainability as essential, adopting a more conservative benchmark (i.e. lower F) such as F_{msy} for elasmobranchs would be more defensable than F_{lim}.

We generally support the earlier recommendations from Zhou *et al*. (2019). In summary, we rephrase the following recommendations:

(1) Adopt $B_{lim} = 0.25B_0$ and corresponding $F_{lim} = 1.5F_{msy}$ as LRPs for WCPO elasmobranchs. Similar metrics apply to both stocks assessed by integrated stock assessments and risk-based assessment. For the former, reference points estimated in the same stock-assessment should be adopted. For stocks using risk-based assessment the combined LRP (cF_{lim}) derived from multiple methods should be used as interim LRPs and the estimates should be reviewed and updated in three to five years when new methods or additional data become available.

(2) If the Commission regards that species interactions and ecological sustainability are essential elements in fisheries management, a relative lower fishing mortality benchmark such as F_{msy} should be considered as LRP for predatory elasmobranchs.

(3) If spawning potential ratio approach is used, calculate the appropriate percentage for each stock. Do not use a constant percentage of SPR such as $F_{60\%SPR}$ as a reference point for all stocks.

(4) The risk-based ERA approach not only provides methods for estimating reference points but also for estimating fishing mortality rate. Fishing mortality is derived from the spatial overlap between fishing effort and species distribution. Such area-based methods have been developed and applied to three WCPO elasmobranchs. This type of tools can be flexibly modified to suit the available data and are recommended for other data-poor elasmobranch stocks.

(5) It is important to continue research to provide or improve estimates of life-history parameters. A meta-analysis could be considered to integrate studies on growth, maturity, and other LHPs from sampling across the whole population in the WCPO.

(6) Selectivity should be estimated for all elasmobranchs in the WCPFC jurisdiction. If selectivity cannot be modelled, a knife-edge size of entry may be determined by length samples of the observed catch.

References

Brodziak, J., Ianelli, J. N., Lorenzen, K., and Methot, R. D. 2009. Estimating Natural Mortality in Stock Assessment Applications. Estimating natural mortality in stock assessment ap- plications. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-119. 38 pp.

Brooks, E. N., and Powers, J. E. 2007. Generalized compensation in stock-recruit functions: Properties and implications for management. ICES Journal of Marine Science, 64: 413–424.

Brooks, E. N., Powers, J. E., and Cortés, E. 2010. Analytical reference points for age-structured models: Application to data-poor fisheries. ICES Journal of Marine Science, 67: 165–175.

Carvalho, F., and Sippel, T. 2016. Direct estimates of gear selectivity for the North Pacific Blue Shark using catch-at-length data: implications for stock. ISC/16/SHARKWG-1/13. 10 pp.

Clarke, S., and Hoyle, S. 2014. Development of limit reference points for elasmobranchs. WCPFC-SC10-2014/ MI-WP-07. Scientific Committee Tenth Regular Session,Majuro, Republic of the Marshall Islands, 6-14 August 2014. 43 pp.

Clarke, S., Coelho, R., Francis, M., Ka, M., Kohin, S., Liu, K.-M., Simpfendorfer, C., *et al.* 2015. Report of the Pacific shark life history expert panel workshop, 28-30 April 2015. Scientific Committee 11th Regular Session, Pohnpei, Federaed States of Micronesia. WCPFC-SC11-2015/ EB-IP-13. 111 pp.

Clarke, S., Langley, A., Lennert-Cody, C., Aires-da-Silva, A., and Maunder, M. 2018. Pacific-wide Silky Shark (Carcharhinus falciformis) Stock Status Assessment. Scientific Committee 14th Regular Session, Busan, Republic of Korea. WCPFC-SC14-2018/ SA-WP-08. 67 pp.

Cortes, E. 2016. Perspectives on the intrinsic rate of population growth. Methods in Ecology and Evolution, 7: 1136–1145.

Cortés, E. 2002. Incorporating uncertainty into demographic modeling: application to shark populations and their conservation. Conservation Biology, 16: 1048–1062.

Cortés, E., and Brooks, E. N. 2018. Stock status and reference points for sharks using data-limited methods and life history. Fish and Fisheries, 19: 1110–1129.

DAWR. 2018a. Commonwealth Fisheries Harvest Strategy Policy. Department of Agriculture and Water Resources, Canberra, Australia, June. CC BY 4.0.

DAWR. 2018b. Guidelines for Implementation of the Commonwealth Fisheries Harvest Strategy Policy. Department of Agriculture and Water Resources, Canberra, Australia, June. CC BY 4.0.

Dowling, N. a., Smith, D. C., Knuckey, I., Smith, A. D. M., Domaschenz, P., Patterson, H. M., and Whitelaw, W. 2008. Developing harvest strategies for low-value and data-poor fisheries: Case studies from three Australian fisheries. Fisheries Research, 94: 380–390.

Francis, M. P., Campana, S. E., and Jones, C. M. 2007. Age under-estimation in New Zealand porbeagle sharks (Lamna nasus): is there an upper limit to ages that can be determined from shark vertebrae? Marine and Coastal Fisheries, 58: 10–23.

Fu, D., Rou, M.-J., Clarke, S., Francis, M., Dunn, A., Hoyle, S., and Edwards, C. 2018. Pacific-wide sustainability risk assessment of bigeye thresher shark (Alopias superciliosus). Prepared for Western and Central Pacific Fisheries Commission. NIWA, Wellington, April 2018. 102 pp.

Gabriel, W. L., and Mace, P. M. 1999. A review of biological reference points in the context of the precautionary approach. Proceedings of the fifth national NMFS stock assessment workshop: providing scientific advice to implement the precautionary approach under the Magnuson-Stevens fishery conservation and management act. NOAA Tech Memo NMFS-F/SPO-40: 34–45. http://oarfish.nmfs.noaa.gov/StockAssessment/workshop_documents/nsaw5/gabriel_.pdf%5Cnpapers2://publication/uuid/6EAF77B6-B72F-48BC-897A-B527149EEFCD.

Garcia, S. M., Kolding, J., Rice, J., Rochet, M. J., Zhou, S., Arimoto, T., Beyer, J. E., *et al.* 2012. Reconsidering the consequences of selective fisheries. Science, 335: 1045–1047.

Grant, M. I., Smart, J. J., White, W. T., Chin, A., Baje, L., and Simpfendorfer, C. A. 2018. Life history

characteristics of the silky shark Carcharhinus falciformis from the central west Pacific. Marine and Freshwater Research, 69: 562–573.
Hamady, L. L., Natanson, L. J., Skomal, G. B., and Thorrold, S. R. 2014. Vertebral bomb radiocarbon suggests extreme longevity in white sharks. PLoS ONE, 9: 1–8.
Harry, A. V. 2018. Evidence for systemic age underestimation in shark and ray ageing studies. Fish and Fisheries, 19: 185–200.
Hoyle, S. D. S. D., Edwards, C. T. T., Roux, M.-J., Clarke, S. C., and Francis, M. P. 2017. Southern hemisphere porbeagle shark (Lamna nasus) stock status assessment. NIWA Client Report, Prepared for Western and Central Pacific Fisheries Commission. WCPFC-SC13-2017/SA-WP-12. 65 pp.
ICCAT. 2010. Report for biennial period, 2008-09 PART II (2009) - Vol. 2 English version. International Commission for the Conservation of Atlantic Tunas. Madrid, Spain. 344 pp.
ISC Shark Working Group. 2018. Stock Assessment of Shortfin Mako Shark in the North Pacific Ocean Through 2016. Scientific Committee 14th Regular Session, Busan, Republic of Korea. WCPFC-SC14-2018/ SA-WP-11. 118 pp.
Kenchington, T. J. 2014. Natural mortality estimators for information-limited fisheries. Fish and Fisheries, 15: 533–562.
Mangel, M., MacCall, A. D., Brodziak, J., Dick, E. J., Forrest, R. E., Pourzand, R., and Ralston, S. 2013. A perspective on steepness, reference points, and stock assessment. Canadian Journal of Fisheries and Aquatic Sciences, 70: 930–940. http://www.nrcresearchpress.com/doi/10.1139/cjfas-2012-0372.
Moe, B. J. 2015. Estimating Growth and Mortality in Elasmobranchs: Are we doing it correctly? Master's thesis: 42. http://nsuworks.nova.edu/occ_stuetd/42.
Myers, R. A., Mertz, G., and Fowlow, P. S. 1997. Maximum population growth rates and recovery times for Atlantic cod, Gadus morhua. Fishery Bulletin, 95: 762–772.
Myers, R. A., and Mertz, G. 1998. The limits of exploitation: A precautionary approach. Ecological Applications, 8: 165–169.
Myers, R. a, Bowen, K. G., and Barrowman, N. J. 1999. Maximum reproductive rate of fish at low population sizes. Canadian Journal of Fisheries and Aquatic Sciences, 56: 2404–2419. http://www.nrcresearchpress.com/doi/abs/10.1139/f99-201.
Neubauer, P., Richard, Y., and Clarke, S. 2018. Risk to the indo-pacific ocean whale shark population from interactions with pacific ocean purse-seine fisheries. Scientific Committe 14th Regular Session, Busan, Korea. WCPFC-SC14-2018/SA-WP-12. 52 pp.
Pardo, S. A., Cooper, A. B., Reynolds, J. D., and Dulvy, N. K. 2018. Quantifying the known unknowns: Estimating maximum intrinsic rate of population increase in the face of uncertainty. ICES Journal of Marine Science, 75: 953–963.
Rice, J., and Harley, S. 2012. Stock assessment of Silky sharks in the western and central Pacific Ocean. Scientific Committee Eighth Regular Session, Busan, Republic of Korea, August 2012. WCPFC-SC8-2012/ SA-WP-07. 53 pp.
Rice, J., Harley, S., and Kai, M. 2014. Stock assessment of Blue Shark in the North Pacific Ocean using Stock Synthesis. August 2014 Majuro, Marshall Islands. WCPFC-SC10-2014/ SA-WP-08. 83 pp.
Sainsbury, K. 2008. Best practice reference points for Australian Fisheries. A Report to Australian Fisheries Management Authority and the Department of the Environment and Heritage. 159 pp.
Semba, Y., Aoki, I., and Yokawa, K. 2011. Size at maturity and reproductive traits of shortfin mako, *Isurus oxyrinchus* , in the western and central North Pacific. Marine and Freshwater Research, 62: 20. http://www.publish.csiro.au/?paper=MF10123.
Shark Working Group. 2017. Stock Assessment and Future Projections of Blue Shark in the North Pacific Ocean through 2015. Scientific Committee 13th Regular Session, Rarotonga, Cook Islands. WCPFC-SC13-2017/ SA-WP-10. 95 pp.
Skalski, J. R., Millspaugh, J. J., and Ryding, K. E. 2008. Effects of asymptotic and maximum age estimates on calculated rates of population change. Ecological Modelling, 212: 528–535.
Takeuchi, Y., Tremblay-Boyer, L., Pilling, G. M., and Hampton, J. 2016. Assessment of blue shark in the southwestern Pacific. Scientific Committee 12th Regular Session, Bali, Indonesia. WCPFC-SC12-2016/ SA-WP-08 Rev1. 1–51 pp.
Tremblay-Boyer, L., Carvalho, F., Neubauer, P., and Pilling, G. 2019. Stock assessment of oceanic whitetip

sharks in the western and central Pacific Ocean. Scientific Committee 15th Regular Session, Pohnpei, Federated States of Micronesia. WCPFC-SC15-2019/SA-WP-06. 98 pp. http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

Zhou, S., Smith, A. D. M., and Fuller, M. 2011. Quantitative ecological risk assessment for fishing effects on diverse data-poor non-target species in a multi-sector and multi-gear fishery. Fisheries Research, 112: 168–178.

Zhou, S., Yin, S., Thorson, J. T., Smith, A. D. M., and Fuller, M. 2012. Linking fishing mortality reference points to life history traits: an empirical study. Canadian Journal of Fisheries and Aquatic Sciences, 69: 1292–1301. http://www.nrcresearchpress.com/doi/abs/10.1139/f2012-060.

Zhou, S., Deng, R., Hoyle, S., and Dunn, M. 2019. Identifying appropriate reference points for elasmobranchs within the WCPFC. Scientific Committee 15th Regular Session, Pohnpei, Federated States of Micronesia. WCPFC-SC15-2019/MI-IP-04. 77 pp.

Zhou, S., Punt, A. E., Lei, Y., Aijun, R., and Simon, D. 2020a. Identifying spawner biomass per-recruit reference points from life-history parameters. Fish and Fisheries, 21: 1–14. https://doi.org/10.1111/faf.12459.

Zhou, S., Liu, C., and Ye, Y. 2020b. Development and performance evaluation of a catch-only method using LHP-based r priors. Final report to FAO. Brisbane, QLD, Australia. Copyright. 88 pp.

Table 1. WCPFC key elasmobranchs species reviewed by the Pacific Shark Life History Expert Panel Workshop (2015, WCPFC-SC11-2015/EB-IP-13)

ID	Stock	Code	Assess yr	Method	RPs on F_{msy}	Ref
1	Blue shark–North Pacific	BSH-N	2017	SS3	0.35 (0.26-0.66)	(Shark Working Group, 2017)
2	Blue shark–South Pacific	BSH-S	2016	Multifan-CL	Results inconclusive	(Takeuchi *et al.*, 2016)
3	Shortfin mako North Pacific	SMA-N	2018	SS3.24U	1-SPR_{msy} = 0.26	(ISC Shark Working Group, 2018)
4	Shortfin mako (South Pacific	SMA-S		Unassessed		
5	Longfin mako	LMA		Unassessed		
6	Silky shark (WCPO)	FAL	2018	SS3.24Z	0.031	(Clarke *et al.*, 2018)
7	Oceanic whitetip (WCPO)	OWT/OCS	2019	SS3.30	0.06	(Tremblay-Boyer *et al.*, 2019)
8	Bigeye thresher (Pacific)	BTH	2017	Quantitative ERA	Based on LHPs	(Fu *et al.*, 2018)
9	Pelagic thresher shark	PTH		Unassessed		
10	Common thresher shark	ALV		Unassessed		
11	Porbeagle shark (Southern hemisphere)	POR	2017	Quantitative ERA	Based on LHPs	(Hoyle *et al.*, 2017)
12	Smooth hammerhead	SPZ		Unassessed		
13	Scalloped hammerhead	SPL		Unassessed		
14	Great hammerhead	SPK		Unassessed		
15	Winghead	EUB		Unassessed		
16	Whale shark (Pacific)	RHN	2018	Quantitative ERA	Based on LHPs	(Neubauer *et al.*, 2018)

Note: (1) ERA is ecological risk assessment; (2) Unassessed stocks are those elasmobranchs that have no stock assessment or quantitative ERA so their stock size and fishing mortality status are unknown.

Table 2. Summary of two reference points (cF_{msy} and cF_{lim}) from three methods for the 15 elasmobranch stocks in the WCPO. L10% and H90% represent the lower and upper bounds of the 80% confidence intervals. Stocks in green, yellow, or red are roughly regarded as high productive, medium productive and low productive species

		cF_{msy}				cF_{lim}			
ID	Stock	Mean	sd	L10%	H90%	Mean	sd	L10%	H90%
1	BSH-N	0.14	0.08	0.05	0.25	**0.21**	0.11	0.08	0.37
2	BSH-S	0.13	0.05	0.06	0.17	**0.19**	0.07	0.09	0.26
15	EUB	0.09	0.04	0.05	0.14	**0.14**	0.06	0.07	0.22
7	OCS	0.08	0.05	0.03	0.16	**0.12**	0.07	0.05	0.24
14	SPK	0.07	0.03	0.04	0.11	**0.11**	0.05	0.06	0.17
16	RHN	0.07	0.04	0.02	0.13	**0.11**	0.06	0.03	0.19
10	ALV	0.07	0.03	0.04	0.11	**0.10**	0.05	0.06	0.16
6	FAL	0.06	0.03	0.02	0.10	**0.09**	0.05	0.04	0.15
13	SPL	0.05	0.02	0.02	0.08	**0.07**	0.03	0.03	0.12
12	SPZ	0.05	0.04	0.00	0.10	**0.07**	0.06	0.00	0.14
11	POR	0.04	0.03	0.01	0.07	**0.06**	0.04	0.01	0.11
3	SMA-N	0.04	0.03	0.01	0.07	**0.06**	0.04	0.01	0.11
9	PTH	0.04	0.03	0.01	0.08	**0.06**	0.04	0.01	0.12
4	SMA-S	0.03	0.04	0.00	0.07	**0.05**	0.05	0.00	0.11
8	BTH	0.02	0.04	0.00	0.08	**0.04**	0.06	0.00	0.12
	Mean	0.07	0.04	0.02	0.11	0.10	0.06	0.04	0.17

Table 3. Predicted spawning potential ratio at MSY (SPR_{msy}) from life-history parameters for the 15 elasmobranchs in the Western and Central Pacific. L10% and H90% represent the lower and upper bounds of the 80% confidence intervals

ID	Stock	mean	sd	cv	median	L10%	H90%
1	BSH_North	0.671	0.136	0.202	0.671	0.501	0.845
2	BSH_South	0.694	0.134	0.193	0.694	0.523	0.868
3	SMA_North	0.740	0.192	0.260	0.753	0.483	1.000
4	SMA_South	0.846	0.167	0.197	0.888	0.613	1.000
6	FAL	0.535	0.186	0.347	0.545	0.299	0.763
7	OCS	0.595	0.152	0.256	0.598	0.405	0.785
8	BTH	0.836	0.155	0.185	0.862	0.627	1.000
9	PTH	0.701	0.160	0.229	0.707	0.498	0.909
10	ALV	0.717	0.156	0.218	0.722	0.517	0.922
11	POR	0.698	0.177	0.254	0.710	0.480	0.921
12	SPZ	0.908	0.128	0.141	0.980	0.720	1.000
13	SPL	0.736	0.149	0.202	0.742	0.542	0.933
14	SPK	0.640	0.155	0.243	0.646	0.448	0.829
15	EUB	0.620	0.120	0.194	0.620	0.467	0.773
16	RHN	0.881	0.229	0.260	1.000	0.558	1.000
Mean		0.721	0.160	0.225	0.743	0.512	0.903

Table 4. F_{msy} **converted from** SPR_{msy} **for the 15 elasmobranchs in the Western and Central Pacific. L10% and H90% represent the lower and upper bounds of the 80% confidence intervals**

ID	Stock	mean	sd	cv	median	L10%	H90%
1	BSH_North	0.128	0.097	0.762	0.107	0.044	0.231
2	BSH_South	0.121	0.088	0.734	0.103	0.037	0.219
3	SMA_North	0.061	0.087	1.420	0.043	0.000	0.125
4	SMA_South	0.081	0.124	1.524	0.044	0.000	0.201
6	FAL	0.153	0.162	1.053	0.110	0.048	0.271
7	OCS	0.106	0.086	0.812	0.088	0.041	0.179
8	BTH	0.087	0.112	1.292	0.058	0.000	0.205
9	PTH	0.098	0.098	1.000	0.079	0.020	0.185
10	ALV	0.094	0.087	0.927	0.077	0.018	0.178
11	POR	0.064	0.105	1.649	0.044	0.011	0.108
12	SPZ	0.200	0.296	1.481	0.028	0.000	0.689
13	SPL	0.071	0.064	0.901	0.059	0.014	0.136
14	SPK	0.081	0.077	0.946	0.066	0.025	0.144
15	EUB	0.189	0.118	0.624	0.163	0.084	0.317
16	RHN	0.031	0.146	4.789	0.000	0.000	0.034
	Mean	0.104	0.117	1.328	0.071	0.023	0.215

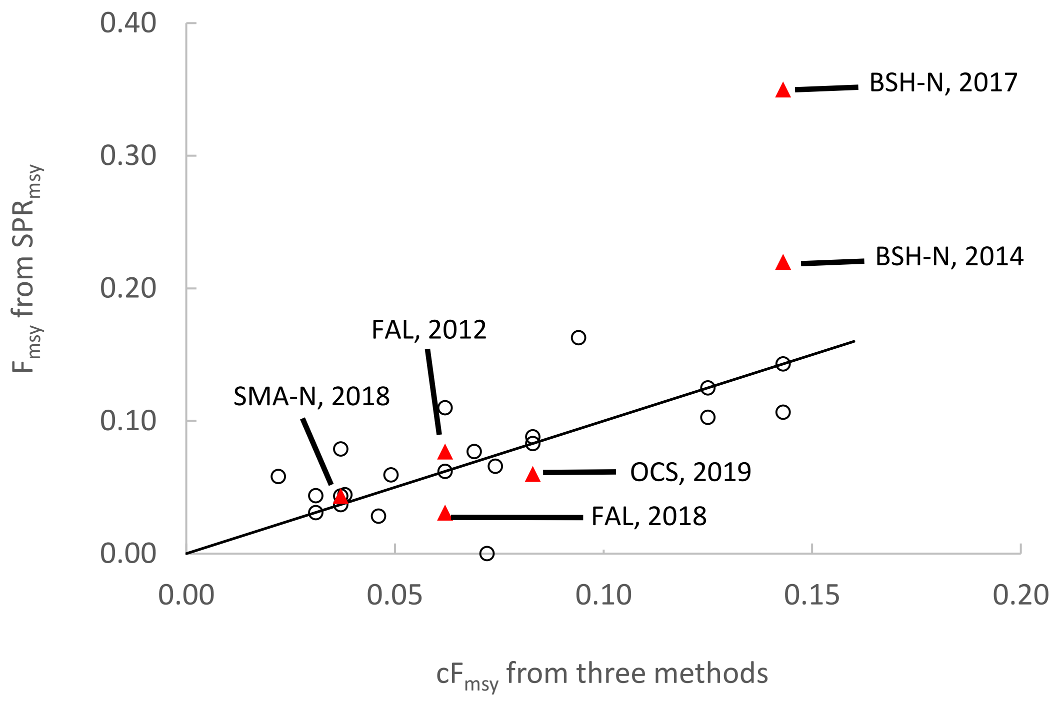

Figure 1. Comparison of reference point F_{msy} from combined three methods and converted from SPR_{msy} (median) for the 15 elasmobranch stocks. The red triangles are F_{msy} estimated by Stock Synthesis (with stock code and assessment year)

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
www.csiro.au

For further information

Oceans and Atmosphere
Shijie Zhou
+61 7 3833 5968
Shijie.Zhou@csiro.au
csiro.au/O&A