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Development of Limit Reference Points for Elasmobranchs

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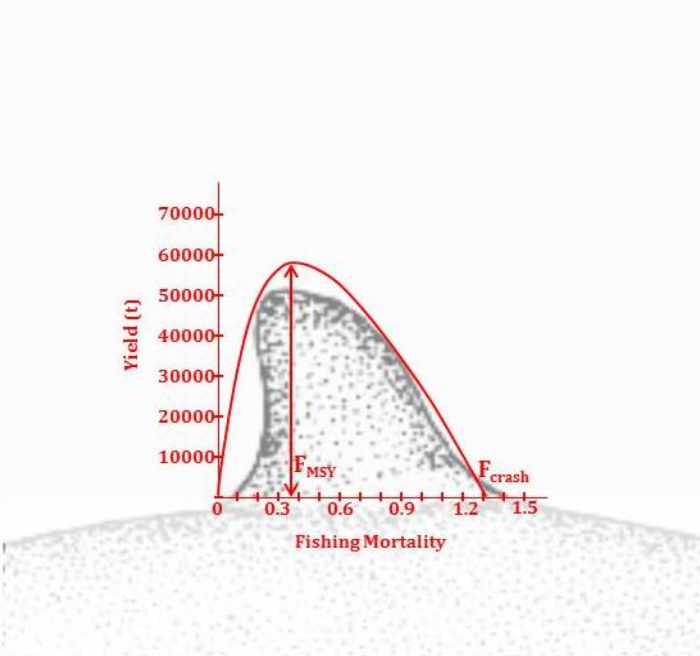

Development of Limit Reference Points for Elasmobranchs

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Abstract

This paper aims to review and recommend appropriate limit reference points (LRPs) for WCPFC elasmobranchs taking into consideration the WCPFC's LRP framework for target species. It provides a conceptual framework for selecting appropriate LRPs for relatively data-poor and under-studied elasmobranch populations while allowing the WCPFC debate on the theoretical advantages and disadvantages of various LRPs to continue. Three broad types of LRPs are defined: i) estimated LRPs which are derived from population models; ii) empirical LRPs that can be directly observed in the field; and iii) risk-based LRPs based on life history parameters alone. After considering a number of expert reviews, and the application of LRPs to sharks and rays in fisheries around the world, this paper recommends 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} is recommended on the basis that it is appropriately conservative and commonly applied as a best practice LRP. However, in cases where the stock-recruitment relationship is highly uncertain, it is recommended that $F_{current}$ also be compared to an SPR-based LRP such as $F_{60\%SPR,unfished}$ so that the WCPFC Scientific Committee can decided on a case-by-case basis which LRP is most appropriate. A biomass-based LRP of $SB_{current}/30\%SB_{dyanmic,unfished}$ is recommended which is similar to the WCPFC-adopted biomass-based LRP for target species but incorporates additional precaution for elasmobranchs by setting the denominator to 30% rather than 20%. When stock assessments are not available, or when the results are not considered robust by the WCPFC Scientific Committee, risk-based fishing mortality LRP benchmarks (F_{msm}, F_{lim} and F_{crash}) used in Australia are recommended. Preliminary calculations for these risk-based benchmarks are presented as an example, but an expert working group should be convened to confirm or re-calculate these based on a full review of the most appropriate life history data. In parallel it will be necessary to develop methods for estimating fishing mortality using a productivity-susceptibility approach in order to derive the numerator for the risk-based LRPs in the absence of a full stock assessment. As development of LRPs is just one element of a comprehensive conservation and management plan for WCPFC elasmobranchs, further work on assessment methodologies, mitigation measures, improved monitoring, and pre-agreed harvest control rules is also recommended.

List of Acronyms

CITES	Convention on International Trade in Endangered Species
CMM	Conservation and Management Measure
ETBF	Eastern Tuna and Billfish Fishery (Australia)
ICCAT	International Commission for the Conservation of Atlantic Tunas
IATTC	Inter-American Tropical Tuna Commission
ICES	International Council for the Exploration of the Sea
IOTC	Indian Ocean Tuna Commission
ISSF	International Sustainable Seafood Foundation
IUCN	International Union for the Conservation of Nature
LRP	Limit Reference Point
MSM	Maximum Sustainable fishing Mortality
MSST	Minimum Stock Size Threshold
MSY	Maximum Sustainable Yield
NOAA	National Oceanic and Atmospheric Administration (United States)
PBR	Potential Biological Removal
RFMO	Regional Fisheries Management Organization
SB	Spawning Biomass
SPR	Spawning Potential per Recruit
SRR	Stock-Recruit Relationship
SSB	Spawning Stock Biomass
SSF	Spawning Stock Fecundity
SSI	Stock Status Indicators
TRP	Target Reference Point
WCPFC	Western and Central Pacific Fisheries Commission

1. Introduction

Frequent fishery interactions and high vulnerability place sharks and rays in a unique and problematic situation

The last decade has seen growing global concern about the status of elasmobranch populations, particularly due to their intrinsic sensitivity to fishing impacts and their very low population growth rates (Dulvy et al. 2014). In parallel, the world's tuna regional fisheries management organizations (t-RFMOs) are increasingly grappling with the challenge of assessing and managing these species. On one hand, elasmobranch catches in some tuna fisheries are as high as, or higher, than target tuna species and the return from elasmobranch products (either fins and/or meat) may be a substantial source of revenue (Clarke et al. 2013, Francis et al. in prep.). On the other hand, as elasmobranchs are only rarely considered to be target species, catch reporting has historically been deficient leading to underestimation of mortalities and considerable uncertainty in assessments (Clarke et al. in prep). As a result, elasmobranchs occupy a unique and problematic position in tuna fisheries: their catch rates are much higher than other vulnerable bycatch organisms such as turtles, seabirds or marine mammals, but data quality can be equally poor. In comparison to other teleost bycatch species, elasmobranch catch rates may be similar but their vulnerability, due to life history traits, is considerably higher.

Tuna RFMOs have conducted assessments and adopted mitigation measures to protect elasmobranchs

Caught between the need to protect tuna-associated species, and a number of important data gaps that hamper assessment and management, t-RMFOs have adopted a variety of strategies. Most have conducted productivity-susceptibility (ecological risk) assessments (Kirby and Hobday 2007; Cortés et al. 2010; Arrizabalaga et al. 2011; IATTC 2012; IOTC 2012) and some have conducted stock assessments for a few of the most frequently caught species (ICCAT 2005, 2008, 2012a,b; Aires-da-Silva et al. 2013; Rice & Harley 2012, 2013). In addition, elasmobranch mitigation measures have been adopted in the form of prohibitions on shark finning applicable to all species, and various forms of no-retention measures for certain species (Clarke 2013). Both types of measures require operational practices that should reduce mortality rates. As such, they are focused on actions taken by the fishery rather than outcomes experienced by the fish stocks.

Reference points can be used to evaluate whether mitigation measures are effective

A first step in determining whether such mitigation measures are effective in reversing population declines is to quantify the mortality rates under the new mitigation regime (Clarke 2013)[1]. A second step is to evaluate the effect of these mortality rates on the population to determine whether it is growing, remaining stable or declining. Fisheries managers often use benchmarks known as reference points to judge whether the current and projected future state of the stock is acceptable (Sainsbury 2008). At present, none of the t-RFMOs have adopted reference points for any non-tuna species, and only the WCPFC has adopted biomass-based reference points for tunas on a non-interim basis (i.e. other t-RFMOs have interim reference points for some tunas; ISSF 2013a). Beyond the t-RFMOs there are some examples of research into appropriate reference points for elasmobranchs but few examples of operationalizing such reference points

[1] The mortality rate under the new mitigation regime will be determined by natural mortality, fishing mortality from operations not subject to the new mitigation regime (if any), the potential change in fishing mortality with perfect implementation of mitigation, and the degree of implementation.

within a management scheme (see Sections 3-5). By responding to the WCPFC Scientific Committee's desire to explore which reference points may be appropriate for WCPFC key shark species[2] this paper endeavours to develop another component of what will eventually be an integrated and comprehensive Conservation and Management Measure (CMM) for elasmobranchs.

The WCPFC is considering developing reference points for elasmobranchs

The terms of reference for this study were defined by WCPFC as follows[3]:

- Document a comprehensive review of limit reference points commonly used for elasmobranchs, especially for WCPFC key shark species in CMM 2010-07[4];
- Assess and document the major benefits and limitations of the limit reference points; and
- Taking into account the limit reference point framework adopted by the WCPFC for target species, recommend a suite of limit reference points for elasmobranchs.

Three steps in developing reference points include selection of type, selection of values, and management implementation

Davies and Basson (2009) describe three phases in the development of reference points. These phases involve selecting the types of reference points that are most appropriate, defining the values of those reference points, and determining how those reference points will be operationalized within the management system. Each phase requires extensive discussion with stakeholders in order that each element is well-understood and accepted. This paper represents the first attempt to define reference points for elasmobranchs within a t-RFMO framework and thus focuses on the first phase. It starts by defining and providing a typology for reference points in the context of WCPFC elasmobranch stocks. Each type of reference point in the typology is then described in terms of its theoretical background and application in other fisheries, and an example of how it could apply to the WCPFC key shark species is provided. After discussing the advantages and disadvantages of each approach, including the data available to support it, recommendations are formulated.

This paper focuses on selecting the appropriate type of reference point—how these should be applied will require further work

The recommendations contained in this paper are intended as a starting point for further analysis and discussion under Davies & Basson's (2009) steps 2 and 3. Specifically, more work will be required to i) refine the values of the candidate reference points; and ii) test the effectiveness of the candidate reference points and yet-to-be developed decision rules in achieving the management objectives. With regard to the first point, while the authors are familiar with the WCPFC's shark data holdings, this study did not access these data directly, rather it relied on existing data analyses already in the public domain. Therefore, the indicative applications of the various types of reference points presented here would benefit from testing against the full set of WCPFC shark data and from consultation with species-specific experts once candidate reference points are identified. With regard to the second point, much of the existing literature on this subject stresses the importance of thoroughly evaluating candidate

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[2] The WCPFC key shark species are blue (*Prionace glauca*), silky (*Carcharhinus falciformis*), oceanic whitetip (*C. longimanus*), mako (*Isurus* spp.), thresher (*Alopias* spp.), porbeagle (*Lamna nasus*; south of 20°S, until biological data shows this or another geographic limit to be appropriate), hammerhead sharks (winghead (*Eusphyra blochii*), scalloped (*Sphyrna lewini*), great (*S. mokarran*) and smooth (*S. zygaena*)), and whale shark (*Rhincodon typus*).

[3] WCPFC Circular 2013/103 dated 9 October 2013

[4] It is noted that in addition to the WCPFC key shark species designated in CMM 2010-07, the WCPFC also adopted whale shark as a key shark species at WCPFC9 (WCPFC9 Summary Report, Attachment J).

reference points using a management strategy evaluation approach. This type of testing would involve using an operating model to evaluate: i) the effects of model assumptions and process error in the population model; ii) an observation model to evaluate observation error in the data; and iii) a management model to explore implementation error in the management procedures, to determine whether the candidate reference points are overly conservative or insufficiently precautionary (Moore et al. 2013).

2. Reference Point Definition and Typology

A reference point is a type of indicator with a current value and benchmark value

A reference point is a quantitative expression of the state of a fishery or population corresponding to a situation that is important for management (*sensu* Caddy & Mahon 1995, Sainsbury 2008). Identification of a reference point thus requires both i) selection of an indicator, or type of quantity that can be measured or estimated (e.g. the estimate from a stock assessment of spawning stock biomass, SSB); and ii) a value of that indicator (e.g. 20% of the initial unfished spawning stock biomass (SSB_0)) to serve as a benchmark. Applying the reference point involves comparing the benchmark to the current (or projected) value of the indicator.

This paper focuses on limit, or conservation, reference points which set boundaries to constrain harvesting within safe biological limits

Reference points can be broadly classified into two categories: target reference points (TRPs) and limit reference points (LRPs). TRPs specify the desired outcomes of fishery management, e.g. optimum yield, as determined through fisheries governance processes. As WCPFC fisheries are not managed in order to achieve particular production goals for sharks, TRPs were not included in the terms of reference for this study and will not be discussed further in this paper. Instead, the focus of this paper is on LRPs used to set boundaries so that harvesting can be constrained within safe biological limits. Because LRPs are set with regard to ecological constraints they are sometimes referred to as conservation reference points (United Nations 1995). A third type of reference point, i.e. a trigger reference point, is sometimes defined to reflect points at which a pre-determined management decision is initiated (Sainsbury 2008). Trigger reference points are not discussed further in this paper as they are designed to reflect the acceptable level of risk that reference points would be breached and are thus a management issue, rather than a scientific one (Berger et al. 2013b). When considering the technical LRPs proposed in this paper it is important to bear in mind that it may be desirable to buffer their boundaries by triggering a management action before an LRP is reached, either by adopting trigger reference points or another means. This issue should be considered in the development of harvest control rules.

Limit reference points (LRPs) are often defined in pressure (overfishing) – state (overfished) pairs

A single stock will often have a pair of LRPs: one each to identify and prevent i) overfishing; and ii) the stock being in an overfished state. Fishing mortality-based LRPs are advantageous because F is more directly controlled by fisheries managers, while biomass-based LRPs more closely reflect the actual ecological status of the population (Sainsbury 2008). Having a pair of LRPs that represent pressure and state, respectively, allows for different management actions to be taken if overfishing is occurring or stocks are in an overfished condition. Finally, there will always be uncertainty in the estimation of fishing mortality and biomass. Therefore, management with respect to LRPs should be precautionary and risk-averse, e.g. through adopting trigger reference points or by incorporating managers' desired level of risk into the LRP itself. Stocks should be managed such that there is a very low (but non-zero) probability the LRPs will be breached and risks associated with approaching a LRP should be recognized, even if the LRP is not breached. Choosing an appropriate level of probability of breaching the LRP is a management issue, and is not addressed in this paper.

There are many outstanding issues regarding tuna LRPs; LRPs for data-poor elasmobranchs face these and other issues

Discussion of candidate elasmobranch LRPs below draws from the extensive body of work on the development of LRPs for WCPFC tuna species (Davies & Basson 2009; Harley et al. 2009; Norris 2009; Campbell 2009, 2010; Davies & Harley 2010; Harley & Davies 2011; Preece et al. 2011; Harley et al. 2012; Berger et al. 2013a,b; and NRIFSF 2013). It also refers to expert summaries of the state-of-the-art for LRPs in many different fisheries worldwide (e.g. Sainsbury 2008, Moore et al. 2013 and ISSF 2013a,b). While taking note of the continuing progress toward LRPs for tunas and other species, this paper recognizes the outstanding issues in that debate and the additional uncertainty that arises when dealing with relatively data-poor and under-studied elasmobranch populations. As a result, this paper focuses on providing a conceptual framework for selecting appropriate LRPs for elasmobranchs, while allowing technical debates on the theoretical advantages and disadvantages of various LRPs to continue.

For simplicity, of the dozens of LRPs that have been applied in fisheries worldwide, three broad types of LRPs will be discussed in this paper:

- Estimated LRPs;
- Empirical (Observable) LRPs; and
- Risk-based LRPs

Three types of single-species LRPs will be discussed: estimated, empirical and risk-based

After presenting the background and theory for each type of LRP, existing application in other fisheries and potential application to WCPFC elasmobranchs is presented below. While it is noted that some of the LRPs reviewed below have been developed for target species, they are still relevant to consideration of LRPs for elasmobranchs because LRPs in general seek to define ecological limits that are based on biology rather than economics and would apply regardless of whether a species is targeted. Furthermore, despite persuasive arguments that LRPs for predatory fishes must take account of how population parameters would shift in response to prey biomass (Gislason 1999, Collie & Gislason 2001), multispecies reference points are in an early stage of development and are characterized by a high level of scientific uncertainty (Sainsbury 2008). Therefore, all of the LRPs discussed below are designed to be applied to a single stock.

3. Estimated LRPs

3.1. Background and Theory

LRPs that are derived from population models are classified in this study as estimated LRPs. Examples of indicators used in estimated LRPs include relative fishing mortality ($F_{current}/F_{MSY}$) and relative spawning biomass

Estimated LRPs are those which are derived from population models and three common indicators are MSY, SPR and depletion

($SB_{current}/SB_{unfished}$); corresponding examples of reference points could include $F_{current}/F_{MSY}$ =1 and $SB_{current}/SB_{unfished}$ =0.2, respectively. Most LRPs developed for and implemented in fisheries management are estimated LRPs. Estimates of $F_{current}$ are usually derived from a stock assessment model, but depending on data availability and quality it may also be possible to derive values of $F_{current}$ from catch curves (Hilborn & Walters 1992), some forms of productivity-susceptibility analysis (Zhou & Griffiths 2008, Zhou et al. 2011) and other methods. Estimates of $SB_{current}$ would typically be derived from stock assessments.

As outlined by Preece et al. (2011) there are three standard approaches for defining estimated LRPs for overfishing and overfished populations: maximum sustainable yield, spawning potential per recruit (SPR, i.e. the potential lifetime contribution of a single recruit to spawning biomass) and depletion (Table 1).

Table 1. Examples of overfishing and overfished LRPs under three approaches within the category of estimated LRPs.

	Overfishing (pressure) LRPs	Overfished (state) LRPs
Maximum Sustainable Yield	$F_{current}/F_{MSY}=1$	$SB_{current}/SB_{MSY}=1$
Spawning Potential per Recruit (SPR)	$F_{current}/F_{40\%SPRunfished}=1$	$SB_{current}/SB_{40\%SPRunfished}=1$
Depletion	-	$SB_{current}/SB_{unfished}=1$

LRPs using MSY as an indicator can be considered as best practice but only if there is sufficient confidence in the parameter estimates

Maximum sustainable yield (MSY) fishing mortality rates (F_{MSY}) are recommended by Sainsbury (2008) as best practice LRP benchmarks, but only in cases where there are sufficient data and confidence in the model, in particular the stock-recruitment relationship (SRR), to reliably estimate the parameters. In counterpoint, Maunder & Deriso (2014) argue that using F_{MSY} as an LRP is inappropriate because the conceptual basis of F_{MSY} is yield rather than ecologically unacceptable fishing mortality rates, and its value is affected by factors unrelated to biological constraints. They also consider that constraining fishing mortality so that there is a very low probability of exceeding F_{MSY}, especially when assessment uncertainty is high, may be too conservative. It is less common to use MSY biomass levels as LRPs. This may be because there are more straightforward and intuitive options available for biomass-based LRPs, such as depletion relative to unfished biomass.

LRPs can also use spawning biomass per recruit (SPR) as an indicator when the stock recruitment relationship is highly uncertain

In cases where there is insufficient confidence in the SRR, but other aspects of population dynamics can be estimated, LRP benchmarks can be derived using the SPR method. This method uses age-specific growth, mortality, fecundity and selectivity to calculate the fishing mortality rate (F) that would reduce SPR by a given percentage. For example, in Table 1 the benchmark $F_{40\%SPRunfished}$ corresponds to the fishing mortality that reduces SPR to 40% of what it would be under unfished conditions. A similar approach can be taken to calculate the biomass which would result from the SPR being a given percentage of the SPR under unfished conditions (e.g. the benchmark $SB_{40\%SPRunfished}$ in Table 1).

The SPR approach has several advantages over the MSY approach. First, the SRR is not reliably known for any WCPFC stock (although it can be potentially inferred with greater confidence for elasmobranchs than for

SPR-based LRPs have advantages over MSY-based LRPs because they are not dependent on assumptions associated with the SRR and selectivity

tunas (Rice & Harley 2012)), and stock assessments usually examine a range of plausible assumptions. This makes MSY-based estimates considerably more uncertain than SPR-based estimates, and prone to change if the assumed SRR changes. Second, since MSY is based on maximizing yield, changes in the selectivity of the fisheries will change the potential yield and thus change the level of the MSY-based LRP (e.g. F_{MSY}). However, such selectivity changes would not affect the SPR-based LRP. Third, the SPR method addresses the production of spawners, which is directly relevant to biological constraints, while MSY is linked to yield which is neither an objective of LRPs nor a priority for elasmobranch management.

One of the disadvantages of an SPR approach is that the percentage (X%) would need to be adjusted for different groups of species depending on their presumed SRRs

One of the disadvantages of the SPR approach is that the effect of the SRR is not accounted for implicitly and therefore it does not adjust automatically for species with different SRRs. An SPR-based LRP would thus need to be specified with varying levels of the percent SPR unfished for different groups of species which can be assumed to have different SRRs. Given the life history characteristics of most elasmobranchs, the number of recruits would likely fall gradually, but steadily, over a wider range of declining stock sizes whereas teleost fishes with higher reproductive output would likely experience less change in recruitment at mid-range stock sizes but sharper declines at low stock sizes. These differences are represented by the higher steepness values assumed for teleost fishes than for elasmobranchs in the Beverton-Holt SRR. For these reasons, it may be appropriate to use more conservative, i.e. higher, percentage SPRs for groups of elasmobranch species than for teleosts.

Biomass depletion approaches may be sensitive to recruitment shifts but this is arguably less important for elasmobranchs

The third approach to estimated LRPs is to select benchmarks representing biomass depletion. This approach uses outputs from a stock assessment model, or a reasonable proxy, to evaluate the current estimate of spawning biomass against its unfished state (e.g. $SB_{current}/SB_{unfished}$). One strength of this approach is that it appears to be relatively insensitive to uncertainties in the SRR (Preece et al. 2011). One disadvantage is that if recruitment conditions change between the unfished and current period (e.g. due to a regime shift) the utility of this approach may be diminished (Sainsbury 2008)[5]. Despite the importance of these issues for tunas, these features of the depletion approach may have less bearing on its appropriateness for elasmobranchs. This is because it is generally assumed that elasmobranch recruitment is directly related to spawning stock size (Mace et al. 2002, Cortés et al. 2012), rather than environmental conditions.

3.2. Examples from Other Species and Fisheries

Estimated LRPs are the basis for the reference point framework thus far adopted by the WCPFC for tropical tuna species. A hierarchical approach was first adopted by the Commission in December 2011 which delineated LRPs for key target species into Levels 1-3 (Table 2). Level 1 is intended to apply to species for which there is a reliable and precise estimate of steepness (the key parameter in the stock recruitment relationship) and

[5] One approach to resolving this issue is to replace virgin biomass with its dynamic equivalent which in effect adjusts for current recruitment levels.

Level 2 is intended to apply to species which lack this information but for which key biological and fishery variables are reasonably well-estimated (Preece et al. 2011). Level 3 is intended to apply to all other key target species (Berger et al. 2013b).

Table 2. LRPs proposed (in gray) and adopted (in blue) for key target species in the WCPFC as of July 2014. Note that the notation, but not the definition, for the Levels 2 and 3 biomass LRPs has been changed to be consistent with the notation used in this paper (see text footnote 5).

Level	Fishing Mortality LRP	Biomass LRP	Species
1	$F_{current}/F_{MSY}=1$	$SB_{current}/SB_{MSY}=1$	-
2	$F_{current}/F_{x\%SPRunfished}=1$	$SB_{current}/20\%SB_{dynamic10,unfished}=1$	bigeye tuna, yellowfin tuna, South Pacific albacore tuna
3	-	$SB_{current}/20\%SB_{dynamic10,unfished}=1$	skipjack

The two LRPs adopted for WCPFC tunas are based on biomass depletion indicators

In December 2012, the Commission adopted Level 2 and 3 biomass LRPs with a request that the Scientific Committee clarify the method and timeframe to be used for calculating the benchmarks for these LRPs (Table 2)[6]. It was subsequently clarified and adopted that the benchmark would use the average of the estimates for the ten years prior to the current year minus one produced by the most recent stock assessment, and estimates of recruitment would be scaled according to the stock-recruitment relationship. The benchmark $20\%SB_{dynamic10,\ unfished}$ thus is designed to represent 20% of the average theoretical level of spawning biomass that would be present during what is considered the "recent" (10 year) period if no fishing had ever occurred given that environmental conditions, and therefore recruitment, would have fluctuated during this time (Berger et al. 2013a)[7].

MSY and SPR-based indicators for fishing mortality are under consideration for WCPFC tunas

Further work on the Level 2 fishing mortality LRP was undertaken to determine which value of *X* would produce a benchmark that matched the Level 2 biomass LRP benchmark (Berger et al. 2013b). However, scientists requested further guidance on the acceptable level of risk to be factored into the analysis (Berger et al. 2013b, WCPFC 2014) and some WCPFC members questioned whether deriving the Level 2 fishing mortality LRP from the Level 2 biomass LRP is appropriate or whether it should be

[6] The original proposal for the biomass LRP (Preece et al. 2011) used the notation $20\%SSB_0$. However, when WCPFC9 adopted the biomass LRP the notation $20\%SB_{recent,F=0}$ was used. Berger et al. (2013a) subsequently defined the LRP as $20\%SB_{F=0,\ t1\text{-}t2}$ where $t1\text{-}t2$ indicates the timeframe over which the unfished spawning biomass is to be calculated. To promote clarity and consistency in notation and terminology, this paper uses $20\%SB_{dyanmic,unfished}$ to denote the adopted biomass LRP. This terminology represents a situation in which unfished (F=0 or virgin) biomass is calculated by scaling absolute estimated recruitment levels according to the stock-recruitment relationship (Berger et al. 2013a). The time period is understood to be an essential element of the calculation but it does not need to be expressed in the notation. It is suggested that notation of "current" or "recent" in connection with this biomass LRP benchmark be avoided in order to minimize confusion with the present value of the indicator, i.e. $SB_{current}/20\%SB_{dyanmic,unfished}$.

[7] This approach represents an intermediate step between $20\%SB_0$ and $20\%SB_{dynamic,\ unfished}$. The former takes into account changes in spawning biomass due to all causes, but may be triggered unnecessarily if the recruitment regime changes, and SB_0 is difficult to estimate. The latter is easier to estimate and only accounts for the effects of fishing mortality on SB, but may be unduly buffered from the effects of recruitment variation, such as a series of poor recruitments.

determined independently (WCPFC 2014). Work on the WCPFC fishing mortality LRPs is ongoing.

Sainsbury (2008) recommends best practice LRPs of $F_{current}/F_{MSY}$, $F_{current}/F_{60\%SPR}$ and $0.3SB_{unfished}$

Based on an extensive review of global fisheries Sainsbury (2008) concludes that an F_{MSY} benchmark is best practice for fishing mortality LRPs except in cases where data limitations cause MSY estimates to be unreliable. In these cases, using a proxy benchmark of at least $F_{50\%SPR}$ for long-lived and low productivity stocks is recommended, with $F_{60\%SPR}$ recommended for species "suspected of having a particularly low ability to compensate for fishery removals (e.g. those with a very low natural mortality or very low steepness)." Sainsbury (2008) also recommends best practice LRPs for biomass but some of these are premised on having a TRP or refer to the "point at which average recruitment declines" which for elasmobranchs would be difficult to define given the expected low values of steepness. As a consequence, the best practice LRP recommendation from Sainsbury (2008) which appears most pertinent to elasmobranchs is $0.3SB_{unfished}$ which can be assumed to be equivalent to $0.3SB_0$ for stocks that do not show large natural fluctuations or regime shifts. While Sainsbury (2008) argues that this biomass LRP is not overly conservative for stocks with high steepness, he does not address whether it is sufficiently precautionary for low productivity stocks.

ICES has developed a precautionary approach to LRPs but this is not well-suited to WCPFC elasmobranchs

The International Council for the Exploration of the Sea (ICES) has not undertaken stock assessments for sharks per se, but it has pioneered the application of a precautionary approach to setting fishing mortality and biomass LRPs for other species in the northeast Atlantic. The approach first calculates a biomass LRP benchmark at the point where average recruitment begins to decline (or for stocks where the stock-recruitment relationship is not well-known, the lowest spawning biomass in the observed time series). A fishing mortality LRP benchmark is then derived from the biomass LRP benchmark. This fishing mortality LRP benchmark is then converted to a precautionary fishing mortality LRP benchmark (F_{pa}) using a retrospective analysis to choose the highest historically "intended" F that did not result in the "realized" F exceeding the risk threshold of the fishing mortality LRP. A precautionary biomass LRP (SB_{pa}) is also calculated using retrospective analysis as a threshold to ensure that if the spawning biomass is at SB_{pa} it has a low probability of being below the biomass LRP benchmark (Sainsbury 2008). While the ICES method is interesting because of its combination of model-based estimates and retrospective analysis, its reliance on historical data makes it unsuitable for most data-poor shark assessment scenarios.

The United States uses LRPs of $F_{current}/F_{MSY}$ and $B_{current}/(1\text{-}M)B_{MSY}$ for Atlantic sharks

An $F_{50\%SPR}$ LRP has been recommended for elasmobranchs off the US Pacific West Coast

In compliance with the requirements of the Magnuson-Stevens Fishery Conservation and Management Act the United States applies both fishing mortality and biomass LRPs to Atlantic shark stocks. The fishing mortality LRP benchmark is F_{MSY}. The biomass LRP is framed as a minimum stock size threshold (MSST) which is calculated as $(1\text{-}M)B_{MSY}$ where M is an estimate of the natural mortality for the species in question (NOAA 2014). It is noted that for some shark stocks, spawning stock fecundity (SSF, the sum of the number of mature sharks at age multiplied by pup-production at age) or number is used by NOAA as a proxy for biomass since biomass does not influence pup production in sharks. In its Atlantic shark stock assessments the International Commission for the Conservation of Atlantic Tunas (ICCAT) also applies F_{MSY} as a fishing mortality LRP benchmark.

ICCAT uses LRPs of $F_{current}/F_{MSY}$ and $B_{current}/B_{MSY}$ for sharks

However, unlike the United States ICCAT uses SB_{MSY} as its biomass LRP benchmark for sharks (NOAA 2014). On the Pacific coast of the United States, SPR-based LRPs were explored for spiny dogfish (*Squalus suckleyi*) and it was recommended that $F_{50\%SPR}$ be applied as an F_{MSY} proxy LRP (PFMC 2013).

Other MSY, SPR and biomass depletion LRPs have been applied to Atlantic shark stocks but are not formally adopted

Also in the Atlantic Campana et al. (2010) and Brooks et al. (2010) have applied LRPs to shark assessments but these LRPs have no formal status in stock management. Campana et al. (2010) estimated several LRPs for porbeagle sharks in Atlantic Canada. Fishing mortality LRPs included F_{MSY}, F_{col} (sometimes referred to F_{crash} (see Section 5), the fishing mortality that drives the population to extinction), and two levels of SPR reduction ($F_{35\%SPRunfished}$ and $F_{45\%SPRunfished}$). It was noted that both levels of SPR reduction exceeded F_{col} in most model runs and are not safe reference points for porbeagle fisheries. Biomass LRPs evaluated included SB_{MSY} and $0.2SB_{unfished}$. Current porbeagle biomass is below both LRPs (Campana et al. 2010). Brooks et al. (2010) proposed a method for calculating LRPs based on SPR proxies for F_{MSY} for nine data-poor species managed by the United States in the western Atlantic and Gulf of Mexico. The method estimates a form of SPR (SPR_{MER}) from biological parameters and an assumed Beverton-Holt SRR, and then obtains an index of relative depletion by applying a fishery-independent index of abundance to scale the hypothesized depletion at the start of the time series. The results were found to correlate closely with results of recent stock assessments. Although the Brooks et al. (2010) method has the advantage of not requiring a full assessment model, an index of abundance (preferably one that is appropriately standardized and/or fishery-independent) is necessary. One of the potential drawbacks of this method is that it is not likely that such an index exists for most elasmobranch populations.

SPR-like LRPs addressing age structure have also been proposed for sharks but these so far lack benchmarks and implementation

Gallucci et al. (2006) propose an indicator similar to SPR and apply it to short- and long-lived sharks in the northeast Pacific. This indicator involves relating depletion risk to the fraction of reproductive potential removed by harvest, thus linking fishing mortality at age to its effects on age structure and population growth. This method has the advantage of directly assessing threats to the population posed by the harvesting of juveniles, but presumes that fishery selectivities and catches-at-age are well understood. Gallucci et al. (2006) do not propose any LRP benchmarks for the purposes of evaluating the acceptability of changes in reproductive potential.

Maunder & Deriso (2014) have proposed reduction in recruitment as a new indicator which can be expressed as a fishing mortality- or biomass-based LRP

In proposing LRPs for Pacific species managed by the Inter-American Tropical Tuna Commission (IATTC), Maunder & Deriso (2014), like Gallucci et al. (2006) reject traditional MSY- and SPR-based LRPs and propose a new indicator. Their proposed indicator is reduction in recruitment (R), where recruitment can be calculated assuming a Beverton-Holt stock-recruitment relationship with a conservative estimate of steepness and an estimate of stock depletion. They assume, as a starting point, that the LRP benchmark could be a reduction of 50% from unfished conditions ($R_{current}/R_{F=0}$ = 0.5). This benchmark can be converted to a biomass LRP using the stock-recruitment relationship, and then from a biomass LRP to a fishing mortality LRP. The authors suggest this approach would be workable, though slightly more complicated, for sharks.

Australia has adopted $B_{current}/0.5B_{MSY}$ as a LRP

Australia's Harvest Strategy Policy for federal fisheries set a biomass LRP benchmark of $0.5B_{MSY}$ and required that harvest strategies consistent with this policy be implemented by 1 January 2008 (Dowling et al. 2008). However, as noted by Sainsbury (2008), for stocks with low levels of B_{MSY}, -this level may be insufficiently precautionary because halving the population at B_{MSY} could result in an extremely low level of abundance from which recovery may be difficult[8].

IUCN and CITES considerations have prompted suggestions that vulnerable populations are those whose biomass has been depleted to 20-30%

Although not drawn from fisheries management, depletion criteria developed for the International Union for the Conservation of Nature (IUCN) and the Convention on International Trade in Endangered Species (CITES) provide definitions of unacceptable fish stock conditions that can inform the selection of LRPs for sharks. Musick (1999) suggested that a population could be classified as vulnerable under IUCN Red List criteria if it demonstrated a 80% reduction in abundance for low productivity species (e.g. maximum age 11-30 years, r=0.05-0.15, k=0.05-0.15) or a 70% reduction in abundance for very low productivity species (e.g. maximum age >30 years, r<0.05, k<0.05). With regard to CITES listings, FAO (2001) and Mace et al. (2002) also suggested that the threshold for concern for low productivity species would be depletion to 20% and 30%, respectively[9].

3.3. Potential Application of Estimated LRPs to WCPFC Elasmobranchs

3.3.1. Identification of Candidate Reference Points from the Review

The preceding review has identified the following points based on international best practice and consideration of the special requirements of sharks:

$F_{current}/F_{MSY}$=1:

$F_{current}/F_{MSY}$ is a best practice LRP when it can be estimated with confidence

This LRP is often considered a best practice LRP when it can be estimated with confidence. It is currently used for elasmobranch management by the United States and ICCAT, and for other species in many other fisheries around the world. Aside from the difficulties in estimating it robustly, the residual criticisms centre on it being based on yield, which is not relevant to the conservation issues addressed by LRPs, and its sensitivity to changes in fishing selectivity.

$F_{current}/F_{x\%SPRunfished}$=1:

$F_{current}/F_{60\%SPRunfished}$ could be specified as a default LRP for highly vulnerable species

This LRP is commonly used for species where F_{MSY} cannot be estimated with confidence. Its estimation can be complicated by issues associated with defining the appropriate value of X; work on this issue is ongoing in the WCPFC for the main tuna stocks. However, in the absence of research investigating this issue for WCPFC elasmobranchs, a conservative LRP of $F_{current}/F_{60\%SPRunfished}$=1 could be specified as a default LRP for species suspected of having a particularly low ability to compensate for fishery removals.

[8] It is not clear in Sainsbury (2008) and Dowling et al. 2008 whether biomass LRPs refer to biomass or spawning biomass (see Campbell 2010).

[9] Although it is not specified in these references, it is assumed the depletion criteria are unit-free, i.e. they can be measured in total biomass, spawning biomass, numbers, etc.

$SB_{current}/SB_{MSY}=1$:

Biomass-based MSY LRPs may be difficult to implement but the United States' approach of $B_{current}/(1\text{-}M)B_{MSY}$ could be considered

While this LRP is used in some fisheries (e.g. ICCAT, Australia's federal fisheries) it is not considered best practice. Like F_{MSY} it is based on yield rather than conservation issues, and may be difficult to estimate accurately. Furthermore, even if an F_{MSY} LRP was adopted, managing the analogous SB_{MSY} would be difficult because biomass is expected to fluctuate around SB_{MSY} even if it is being fished at F_{MSY}. If, despite these concerns, an MSY-based biomass LRP is desirable, the United States' approach of factoring the benchmark by the natural mortality rate $(1\text{-}M)B_{MSY}$ should be considered.

Biomass depletion from unfished conditions (virgin or dynamic):

A biomass depletion LRP would be consistent with the WCPFC approach to tunas but may need to be more conservatively set at $0.3SB_{unfished}$

The LRPs adopted by the WCPFC for tuna species are biomass depletion LRPs with benchmarks of depletion to 20% of the recent average SB given recent recruitment under unfished conditions ($20\%SB_{dynamic10,\ unfished}$). This benchmark is slightly lower than the recommended best practice benchmark recommended by Sainsbury (2008), i.e. $0.3SB_{unfished}$. A depletion of 30% is also recommended as the threshold of vulnerability when considering species for listing on the IUCN Red List or CITES. For the sake of consistency between elasmobranch and tuna LRPs it would make sense to define the benchmark in terms of $SB_{dynamic10,\ unfished}$, although it is expected that elasmobranchs would be less sensitive than tunas to the change in estimation methods due to their assumed relatively inelastic stock-recruitment relationship.

Other proxies for biomass-based (and fishing mortality) LRPs:

Other LRPs based on fishing mortality will need further work before adoption

Other proxies for biomass-based (and fishing mortality) LRPs have been proposed for elasmobranchs (e.g. SPR_{MER}, reduction in reproduction potential, reduction in recruitment) but they are not yet widely used and some require data inputs (e.g. selectivities, reliable indices of abundance) that are difficult to obtain for sharks and rays. One exception to this could be the new proposal for reduction in recruitment by Maunder & Deriso (2014). However, their initial proposal for a benchmark of $R_{current}/R_{F=0} = 0.5$ will require further consideration.

3.3.2. Trial Application of the Candidate Reference Points to WCPFC Sharks

Information from the two WCPFC-endorsed shark stock assessments (oceanic whitetip (Rice & Harley 2012) and silky (Rice & Harley 2013) sharks) was accessed and evaluated against the candidate estimated LRPs. Quantities were drawn from the shark stock assessment report where possible; quantities that must be recalculated from the model itself were obtained for the publicly available oceanic whitetip model[10]. While it might be possible to calculate some of the quantities needed for the candidate estimated LRPs without having access to a stock assessment model (e.g. SPR quantities in various forms) this was beyond the terms of reference of this study.

[10] Available at http://www.spc.int/oceanfish/en/ofpsection/sam/sam

Fishing pressure on oceanic whitetip and silky sharks breaches the $F_{current}/F_{MSY}$ benchmark

$F_{current}/F_{MSY} = 1$:

The oceanic whitetip stock assessment found that the ratio of $F_{current}/F_{MSY}$ was 6.5 (confidence interval 3-20). This ratio in the silky shark stock assessment was 4.48 (confidence interval 1.41-7.96). In both cases it is concluded that the stocks are clearly being overfished. Although there is considerable uncertainty about the estimates of both $F_{current}$ and F_{MSY}, the conclusion that overfishing is occurring is robust to this uncertainty.

Fishing mortality LRPs in terms of SPR are not available from recent WCPFC shark stock assessments

$F_{current}/F_{60\%SPRunfished} = 1$:

This ratio can be output by the Stock Synthesis model used in the oceanic whitetip and silky shark assessments but was not presented in the assessment reports. Therefore no conclusion can be drawn regarding whether the assessment results would have indicated that this LRP is being breached.

An indicative comparison between the recent oceanic whitetip assessment and an LRP based on removal of recruitment indicates the stock is heavily overfished

$SB_{current}$ = SB corresponding to $R_{current}/R_{F=0} = 0.5$

This indicator was proposed in May 2014 and as such was not included in the oceanic whitetip and silky shark assessments. However, using the publicly available version of the oceanic whitetip shark assessment, and assuming, as in the stock assessment, that steepness = 0.409, the *SB* depletion corresponding to the proposed benchmark ($R_{current}/R_{F=0}$ = 0.5) is 0.265. Given that the oceanic whitetip assessment found a ratio of $SB_{current}/SB_0$ of 0.065, on the basis of this indicator it would be concluded that this stock is heavily overfished. It should be noted that this value will change slightly if recalculated using $SB_{dynamic10,\ unfished}$. An important source of uncertainty associated with the use of this LRP is error in the assumed shape of the stock recruitment relationship (i.e. steepness in these examples). This is a common problem in stock assessments for elasmobranchs and other species, and is not likely to be easily resolved.

Comparison of oceanic whitetip and silky sharks to a biomass MSY LRP suggests the former is overfished and the latter is probably overfished

$SB_{current}/SB_{MSY} = 1$:

This ratio is provided in both oceanic whitetip and silky assessments. For oceanic whitetip sharks the ratio is 0.153 (confidence interval 0.082-0.409), therefore this LRP shows the stock is clearly overfished. For silky sharks the ratio is 0.70 (confidence interval 0.51 - 1.23) suggesting the stock is likely to be overfished but with some probability that the LRP has not been breached and the stock is not overfished.

The biomass depletion indicator used in the oceanic whitetip and silky shark assessments was different to what is proposed here

$SB_{current}/SB_{dynamic,\ unfished} = 0.3$:

This ratio can be output by the Stock Synthesis model used in the oceanic whitetip and silky shark assessments but was not presented in either assessment report. Therefore no conclusion can be drawn regarding whether the assessment results would have indicated that this LRP is being breached. However, as noted above, the oceanic whitetip assessment presents a ratio of $SB_{current}/SB_0$ of 0.065, and the silky shark assessment's value for the same ratio is 0.272. Therefore, if the denominator were SB_0 both stocks would be classified as overfished.

4. Empirical LRPs

4.1. Background and Theory

Empirical LRPs can be directly measured in the field, e.g. catch, catch rate, size, etc.

The second broad type of LRP discussed in this paper is empirical LRPs. The fundamental difference between empirical LRPs and the estimated LRPs described above is that empirical LRPs can be directly measured in the field. Quantities such as catch and catch rate, size (e.g. median length or percentile), spatial range or habitat use (e.g. spawning locations), and sex ratio are examples of empirical indicators (Sainsbury 2008).

The benefits of empirical LRPs include transparency and a closer relationship to monitoring and management

The development of empirical LRPs has been motivated by an acknowledgement that the quantities that have formed the basis of estimated reference points (specifically *F* and *MSY*) are often derived only with substantial effort (e.g. a stock assessment model). Not only is such effort not possible for many fisheries around the world, even within well-monitored fisheries there may be species (e.g. sharks) for which data quantity and quality are too poor to support elaborate assessments (Prince et al. 2011). Furthermore, critics argue that the complexity of the analytical methods obscures the fact that the estimates are often unreliable and do not account for all the structural uncertainty in the models themselves (Hilborn 2002). Empirical reference points are thus advocated as a means of increasing transparency and strengthening the linkage between fisheries monitoring and management feedback control rules (Butterworth 2006).

Developing and testing empirical LRPs can be as, or more, onerous than estimated LRPs

Despite being prompted by a desire for simplification, empirical LRPs can be difficult to develop and test appropriately. First, although they are based on directly measurable quantities, empirical LRPs will still be subject to uncertainty and bias, and modelling may be necessary to smooth and extrapolate sparse data (Punt et al. 2001, Hilborn 2002). Second, in many applications, the goal is to find a relationship between the observable parameter and an undesirable state of the population. This requires construction of a stock assessment or sophisticated operating model to estimate fishing mortality or biomass over a time series (Hilborn 2002, Prince et al. 2011). Third, changes in empirical LRPs can have multiple interpretations and management responses. It is thus essential that indicators, benchmarks and decision rules be thoroughly tested using a management strategy evaluation (or similar) process (Sainsbury 2008). Given all of these issues, it is likely that the developing and testing of an empirical LRP will be no less, and perhaps more, onerous than an estimated LRP. The benefit from the empirical LRP will only be realized if it performs well over time without requiring ongoing intensive analysis.

4.2. Examples from Other Species and Fisheries

Practical experience with empirical LRPs is limited

A prior global review of empirical reference points concluded that practical experience with their reliable application is limited (Sainsbury 2008). In fact, several of the examples of empirical reference points in the literature appear to be focused on using them to achieve stock rebuilding and/or optimal yield (Hilborn 2002, Prince et al. 2011) and as such have a different conceptual basis than what is required for WCPFC elasmobranchs.

Changes in catch or catch rate are used in Australia fisheries to trigger additional research or management

Two examples from Australia describe empirical approaches for fisheries without formal stock assessments. A management system developed for the Coral Sea line, trawl and trap fisheries uses changes in empirical quantities such as catch or catch rate as trigger levels for management action (Dowling et al. 2008). A Level 1 response (exploratory analysis trigger) is invoked when the catch proportion of a species changes by more than a set percentage of its historical average or declines inter-annually by a set percentage over a fixed time period. A Level 2 response (stock assessment trigger) is invoked when a pre-defined decline in catch rate accompanies the Level 1 response. When Level 2 is triggered catch curve analysis is used to estimate fishing and natural mortality and to define mortality-based benchmarks. In this sense, the Dowling et al. (2008) approach does not use empirical indicators to directly assess stock status, rather it uses them as a precursor to applying simplified estimated reference points. While this type of approach could be considered as a component of a management strategy for WCPFC elasmobranchs, it would not, per se, satisfy the objective of determining LRPs.

Changes in catch rate and size were trialed as proxies for when a biomass LRP would be breached for Australian swordfish

In another example Punt et al. (2001) test the relationships between empirical indicators catch rate, length (mean and 95th percentile), and weight (mean and 95th percentile) and an assumed biomass LRP of $0.4B_0$ (virgin biomass) for broadbill swordfish (*Xiphias gladius*) in the eastern tuna and billfish longline fishery (ETBF). The objective of their analysis was to test if any of these parameters can serve as proxies for determining when a population has breached its LRP. The authors built a relatively complex operating model to estimate exploitable biomass over the range of 0.3-$0.5B_0$, and then regressed each indicator against this biomass to obtain its value at $0.4B_0$. The performance of the derived indicator value in representing whether the biomass had breached the LRP was then evaluated through simulation testing. The results showed that due to high inter-annual variability in the catch rate indicator it performed poorly and was triggered at biomass levels well above the LRP (i.e. it was overly sensitive). The length and weight indicators performed better and among these the 95th percentile of length was considered best. However, even this indicator was sometimes triggered too early or too late in the biomass trajectory and its performance varied with the assumptions used in the operating model. Despite the uncertainties associated with both the data and the model used in this approach, it was considered workable and able to be applied in a precautionary manner, e.g. by choosing conservative length benchmarks (Punt et al. 2001). Empirical indicators are currently used as the basis for the harvest strategy in the ETBF and are reportedly welcomed by industry for their simplicity and transparency (Prince et al. 2011).

Empirical indicators will be developed for silky sharks by IATTC as part of a broader management framework

In a recent paper, the IATTC proposed to use empirical stock status indicators (SSI) such as standardized catch rates on floating object purse seine sets to assess and manage silky sharks (Aires-da-Silva et al. 2014). Although this indicator has been identified as the potentially most useful among a suite that were considered, this represents only the first step in Davies & Basson's (2009) outline of LRP development. The IATTC plans to use a management strategy evaluation approach to identify benchmarks and decision rules and to evaluate their performance and reliability (Aires-da-Silva et al. 2014).

4.3. Potential Application to WCPFC Elasmobranchs

A simplified version of the Australian swordfish approach was applied to WCPFC oceanic whitetip sharks

In order to explore whether empirical indicators such as catch rate or length could be used as a basis for LRPs for WCPFC elasmobranchs, a simplified version of the Punt et al. (2001) approach was applied to oceanic whitetip sharks.

Using existing stock assessment results the relationship between catch rate/length and fishing mortality/biomass was modelled

The model and data described in Rice & Harley (2012)[11] were used to predict catch rate and mean length for 100 years into the future in the absence of fishing. This allowed the short time series modelled in the original assessment to be expanded to examine the relationships (i.e. distribution and uncertainty) between these potential indicators and biomass and fishing mortality across a wide range of levels (Figure 1). A long time series without fishing was required to permit biomass to recover from its highly depleted state. Modelling recruitment variability, structural uncertainty, parameter uncertainty, and alternative catch series was beyond the scope of this study, but would be required in work aimed at developing species-specific recommendations.

Based on the observed relationships between catch rate and biomass and length and biomass, the value of each empirical indicator at $0.4B_0$ was identified

Consistent relationships with the potential empirical indicators were observed only for biomass, not for fishing mortality. Therefore, linear modelling was used to estimate the relationships between catch rate and biomass and mean length and biomass (Table 3). The standard errors in these estimates mainly reflect variability in recruitment and fishing mortality. However, since the model timeframe was long (i.e. 100 years) and variability in recruitment and fishing mortality were not modelled in the projection period this analysis underestimates the true variance in these relationships, particularly for mean length. The value of each indicator in the non-target longline fishery when the biomass was at an arbitrarily defined LRP (i.e. $0.4B_0$ as assumed by Punt et al. 2001) was identified as 186.9 cm for size and a catch rate of 0.38 sharks per 1000 hooks. It should be noted that this standardized catch rate is predicted with a zero inflated negative binomial model for a unique combination of vessels, locations, and hooks between floats, and cannot be used independently of the standardization model.

Table 3. Parameters estimated from fitting linear models to the relationships between modelled biomass depletion and the expected values of the potential indicators catch rate and size for oceanic whitetip shark.

Parameter	Estimate	Std. Error	t value	Pr(>|t|)
Catch rate				
Intercept	0.060	0.015	4.06	4.48e-04
Biomass depletion	0.802	0.038	20.94	< 2e-16
Mean Length				
Intercept	176.395	2.068	85.28	< 2e-16
Biomass depletion	26.385	5.333	4.95	4.75e-05

[11] Available at http://www.spc.int/oceanfish/en/ofpsection/sam/sam

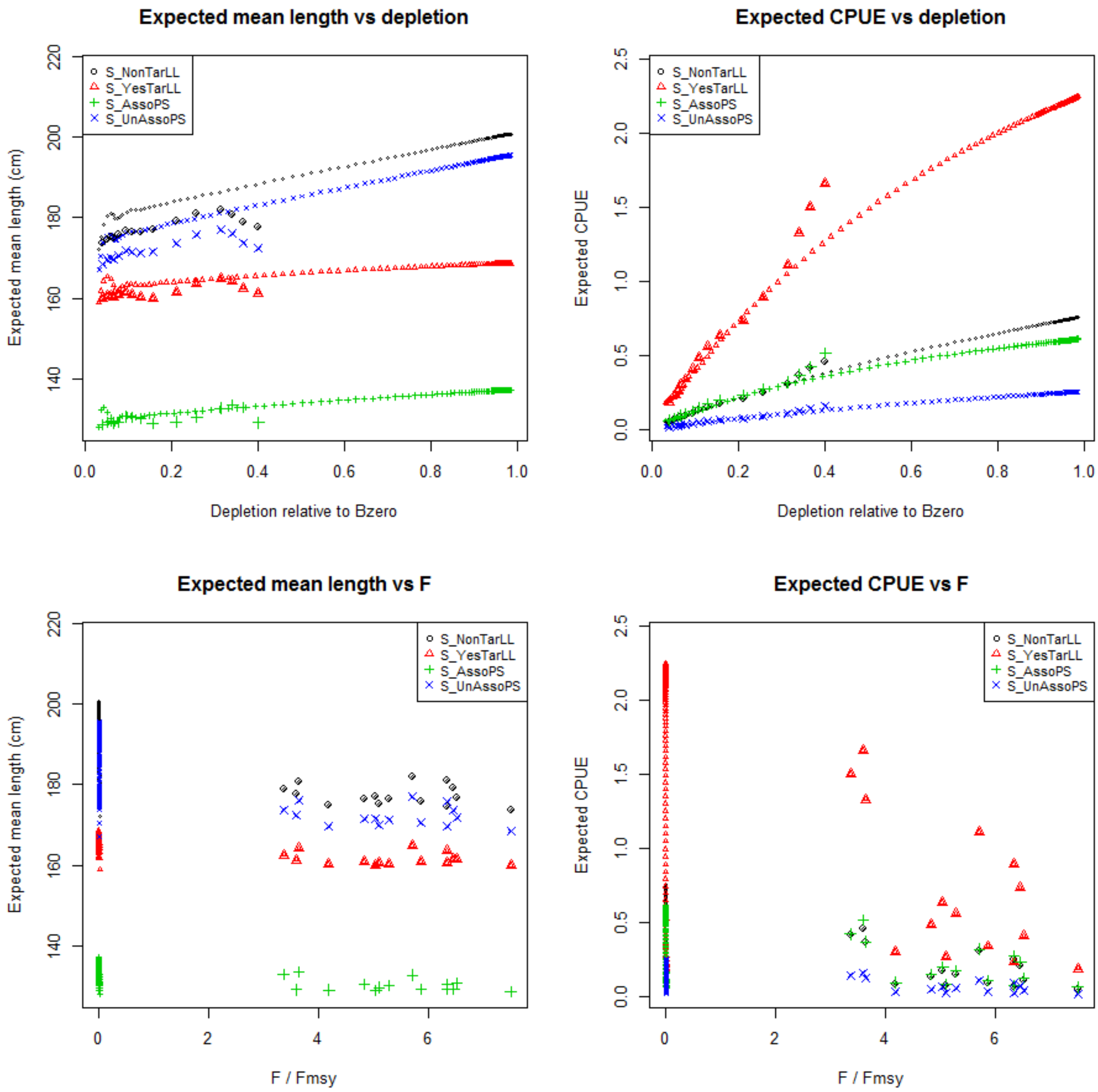

Figure 1. Expected values of the indicators for mean length (left) and catch rate (right) versus biomass (top) and fishing mortality (bottom). Following from the fleets defined in the original assessment (Rice & Harley 2012) values for the non-target longline fishery are shown in black, the shark-targeting longline fishery in red, the associated purse seine in green, and the unassociated purse seine fishery in blue. Large symbols represent values from the observed time series; small symbols are from the projected period with zero catch.

The catch rate indicator was found to be better than the length indicator at identifying when the biomass LRP was breached

The next step involved simulating the distributions of mean length and catch rate at a range of biomass depletion levels to determine the probability that each potential indicator would be below its LRP when the biomass was below the defined level. Three sources of uncertainty were included in this simulation: i) uncertainty in the relationship between the biomass and the indicator (based on sampling from the distribution of the estimate); ii) annual process error between the predicted indicator and its actual value (15% for catch rate based on Francis et al. 2001; arbitrarily 5% assumed for mean length); and iii) observation error in the observed indicators based on results from previous standardization (30% for catch rate (Rice 2012); 9% for length (Clarke et al. 2011)). Results showed that the catch rate indicator was much more sensitive than the mean length indicator in identifying when the biomass breached the assumed LRP (Figure 2). The catch rate indicator's probability of being triggered dropped from 75% at $0.3B_0$ (where it ideally would be 1) to ~30% at $0.5B_0$ (where it ideally would be zero). The relationship between mean length and biomass had considerably less contrast, however, and the indicator had only a 55% probability of being (correctly) triggered at $0.3B_0$ and as much as 45% probability of being (wrongly) triggered at $0.5B_0$. Including additional uncertainty in these simulations, as recommended above, would reduce the sensitivity of both types of indicator.

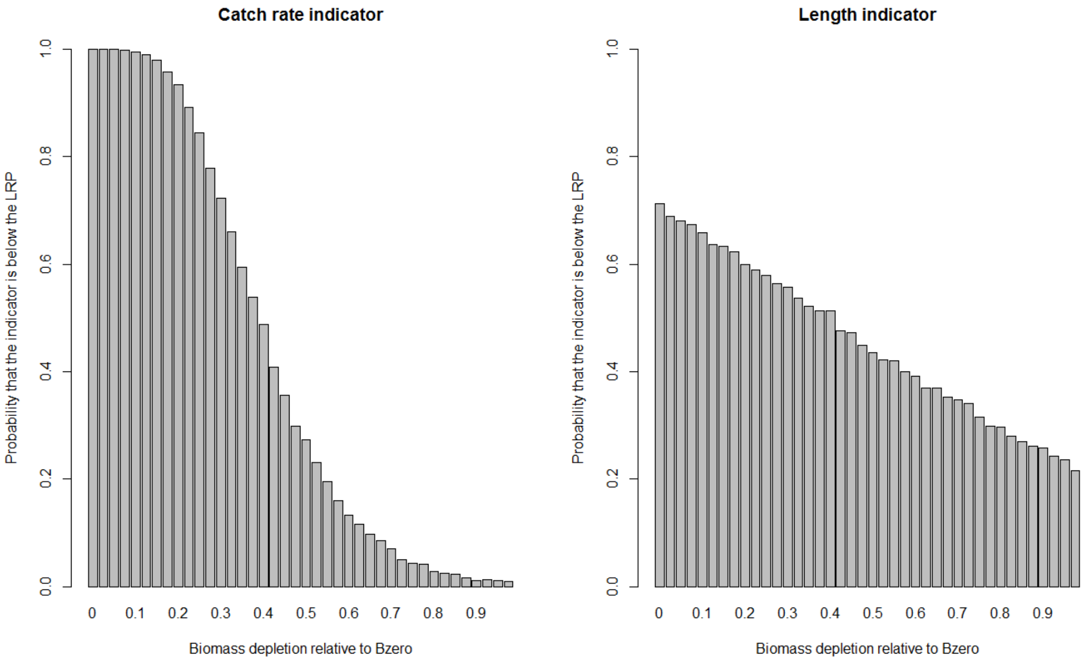

Figure 2. Probability of the two potential indicators, catch rate and mean length, being triggered when biomass ranges from 0-100% of virgin biomass (B_0).

This trial application of empirical reference points for oceanic whitetip shark shows different results to that by Punt et al. (2001) who found a weak relationship between catch rate and biomass and a stronger relationship between length and biomass. Theory suggests that the observation in the present study is likely to be common because catch rate is expected to be proportional to biomass. Aside from the fact that the

Differences between swordfishes and sharks may explain why different empirical indicators were recommended

catch rate series used in the swordfish study was not standardized, a key difference lies in the biology of swordfish as compared to sharks. There may be less signal of a change in the age and size structure of sharks than there would be for teleost fishes where the steepness of the stock recruitment relationship is higher[12]. In sharks recruitment is more closely related to spawner numbers than it is for teleost fishes (Taylor et al. 2013).

Trial development of empirical LRPs shows their potential but indicates that considerably more development work would be necessary

Although this trial has demonstrated that the Punt et al. (2001) method can be applied to develop empirical reference points for WCPFC elasmobranchs it is important to note that its use is premised upon there being i) a stock assessment (or operating) model available to estimate unfished biomass; and ii) data on the values of the potential indicators at a range of unfished biomass levels. Furthermore, the method depends on establishing a strong relationship between the indicator (e.g. catch rate) and the state of the population and this may not always be possible either because such a tight relationship does not exist, or because uncertainties in the model or in the data hamper its estimation. For example, models use selectivity curves, growth parameters and stock recruitment relationships, some of which may be highly uncertain for shark species. Such modelling exercises also rely on observational data being reasonably precise and representative whereas in many cases for sharks sample sizes are limited and may include only selected stock strata. A final issue is that this approach illustrates how an empirical indicator can be determined for a pre-existing indicator (e.g. biomass depletion compared to B_0, as estimated in an assessment model). Since no LRPs have been yet agreed for WCPFC elasmobranchs, adopting an empirical indicator approach would imply a two-step process to agree the initial indicator and then its proxy. In conclusion, the Punt et al. (2001) method has the potential to help define LRPs for WCPFC elasmobranchs but it would require considerable initial development work, particularly for those species without existing stock assessment models. Its main benefits would be in alleviating the need to conduct repeated stock assessments and providing a simple and transparent basis for management.

Applying this approach would require adopting an LRP and then identifying and agreeing an appropriate proxy empirical indicator

5. Risk-based LRPs

5.1. Background and Theory

Benchmarks for risk-based LRPs can be calculated from a handful of life history parameters alone

The third and final type of reference point reviewed in this paper is based on applying a risk-based approach to life history parameters. Although estimated LRPs derived from population dynamics models (see Section 3) also use life history parameters such as growth rates and age at maturity, they usually require fishery statistics, or assumptions about these fishery statistics, which may not be available or reliable for elasmobranch species. In contrast, benchmarks for risk-based LRPs can be calculated from a handful of life history parameters alone.

One potential disadvantage of risk-based LRPs is that research to date has focused on evaluating the sustainability of fishing mortality, and thus on the 'pressure' (overfishing) rather than the 'state' (overfished) of the stock.

[12] Values of steepness ranging from 0.6-0.9 are assumed in WCPFC tuna stock assessments whereas a steepness of 0.41 was assumed in the oceanic whitetip shark stock assessment.

Risk-based LRPs heavy reliance on life history parameters such as natural mortality and the intrinsic rate of increase can be a disadvantage if these parameters are not well-known for each species

Another issue is their heavy reliance on species-specific natural mortality (M) or intrinsic rate of increase (r) values. This feature is in some senses a benefit because estimates of such values are available for most fishes, even those which are data-poor (e.g. Fishbase 2014). At the same time this reliance is a methodological disadvantage if the available life history parameters are poorly estimated, for example, extrapolated from other species or based on a very small number of samples. Risk-based methods also rely on simplified relationships between life history parameters and population dynamics. Therefore lack of accounting for age-based selectivity, density dependence and deviations from a symmetric surplus production model may be a concern when applying risk-based methods to elasmobranchs (Zhou et al. 2012, Moore et al. 2013).

Risk-based LRPs can also be applied to stock assessment outputs

It should be noted that it is possible for a risk-based LRP approach to be combined with an estimated LRP approach. For example, for those species with stock assessments the current fishing mortality estimated using the stock assessment could be compared to risk-based LRP benchmarks as well as to traditional estimated LRPs like F/F_{MSY} produced by the stock assessment. For those species without stock assessments, under the risk-based LRP approach, the current fishing mortality can be estimated using some forms of productivity-susceptibility analysis (Zhou and Griffiths 2008, Zhou et al. 2011)[13]. These alternative F estimates could then be compared to the risk-based LRP benchmarks. In summary, the risk-based approach provides an alternative to a population dynamics model approach, but if desirable for consistency the risk-based LRP benchmarks can also be applied to stock assessment outputs.

5.2. Examples from Other Species and Fisheries

An Australian risk-based approach generates F from productivity-susceptibility analyses and compares it to three fishing mortality LRPs

Risk-based approaches to assessing the effects of fishing have been pioneered by Australian researchers to overcome data gaps hindering the management of non-target species (Zhou & Griffiths 2008, Zhou et al. 2011). Examples are provided for assessment of a longline fishery (though not for elasmobranchs) and elasmobranchs caught in a trawl fishery (Zhou et al. 2011). These methods involve comparing LRP benchmarks defined using life history parameters to fishing impact estimated using productivity-susceptibility analysis. However, as noted above, it is possible to estimate F in other ways and still compare to the same LRP benchmark.

Three LRPs are formulated:

- F_{msm} = instantaneous fishing mortality rate that corresponds to the maximum number of fish in the population that can be killed by fishing in the long term[14]. This represents the maximum sustainable fishing mortality (MSM) at B_{msm} (biomass that supports MSM), similar to target species MSY;

[13] This paper acknowledges that productivity-susceptibility analysis (PSA) can produce current (or projected) values of fishing mortality that can be compared against fishing mortality LRP benchmarks. However, just as it does not review the various available stock assessment models, it also does not review PSA methodologies or evaluate their advantages and disadvantages.

[14] F_{msm} can be considered to approximate F_{MSY} (Zhou et al. 2012).

- F_{lim}: the instantaneous fishing mortality rate that corresponds to the limit biomass B_{lim}, where B_{lim} is assumed to be half of the biomass that supports a maximum sustainable fishing mortality; and
- F_{crash}: the minimum unsustainable instantaneous fishing mortality rate that, in theory, will lead to population extinction in the long term.

Each LRP is calculated using six different methods, all of which were given equal weight

Each is calculated in six ways using different combinations of life history parameters (Table 4). Zhou et al. (2011) applied as many of the six methods as possible to 499 species, 99 of which were chondrichthyans, based on the data available for each. All six methods were able to be applied for 44% of the species. Method 1 was considered the most defensible theoretically, but not necessarily the most reliable in terms of the data quality, therefore all methods were given equal weight when calculating F_{lim} and F_{crash}.

Exceedance of the lowest LRP is considered to indicate overfishing; exceedance of the two higher LRPs is considered high and extremely high risk

If the *F* for each species is greater than F_{msm} then overfishing is occurring. Exceedance of F_{lim} is considered high risk and exceedance of F_{crash} is considered extremely high risk (Zhou et al. 2011).
Zhou et al. (2011) consider that their method is quantitative, flexible, and transparent as well as cost-effective because its data requirements are low (e.g. it does not require relative abundance or size structure information). This method, in various forms, has been used to assess and manage a number of Australian fisheries (AFMA 2014).

Table 4. Six methods used to calculate LRP benchmarks for fishing mortality indicators F_{msm}, F_{lim} and F_{crash} using life history parameters (Zhou et al. 2011). ω is a coefficient linking fishing mortality to natural mortality. It was estimated as 0.43 for elasmobranchs in Zhou et al. (2011) but subsequently revised to 0.41 (standard deviation=0.09) based on a meta-analysis comparing fishing mortality LRPs F_{MSY}, $F_{0.1}$ and $F_{0.5r}$ (Zhou et al. 2012).

Method	Formula for F_{msm}	Formula for F_{lim}	Formula for F_{crash}	Parameters
1	$r/2$	$0.75r$	r	r = intrinsic population growth rate
2	ωM	$1.5\omega M$	$2\omega M$	M = an existing estimate of instantaneous natural mortality
3	ωM	$1.5\omega M$	$2\omega M$	$\ln(M)$=-0.0152-0.279$\ln(L_\infty)$+ 0.6543$\ln(K)$+ 0.4634$\ln(T)$ where L_∞ and K are von Bertalanffy growth parameters, and T is average annual water temperature
4	ωM	$1.5\omega M$	$2\omega M$	$\ln(M)$=-1.44-0.982$\ln(t_m)$ where t_m is maximum reproductive age
5	ωM	$1.5\omega M$	$2\omega M$	$M=10^{0.566-0.718\ln(L_\infty)}+0.02T$ where L_∞ is from the von Bertalanffy growth equation and T is average annual water temperature
6	ωM	$1.5\omega M$	$2\omega M$	$M=1.65/t_{mat}$ where t_{mat} is average age at maturity

An alternative type of risk-based approach is embodied in the concept of Potential Biological Removal (PBR; Wade 1998). The United States' Marine Mammal Protection Act applies this concept to define the acceptable number of human-induced mortalities that will allow the population to reach or maintain its optimum sustainable level[15]. PBR is calculated from a minimum population estimate of the stock, half the maximum net productivity rate at a small population size; and a recovery factor of between 0.1 and 1.0 according to the formula:

$$PBR = N_{min} \times 0.5R_{max} \times recovery\ factor$$

Potential Biological Removal defines acceptable human-induced mortalities to marine mammals but its application to elasmobranchs is limited by the need for a population estimate

The ratio of removals (PBR) to the minimum population estimate (N_{min}) is equivalent to a fishing mortality rate, and R_{max} is equivalent to the intrinsic rate of increase, r (Zhou et al. 2011). The recovery factor is the least empirical of the parameters because it is set to represent both the degree of bias in the population estimate and the acceptable level of risk. Consultation and simulation testing conducted in the development of PBR suggested a recovery factor of 0.5 would be adequately precautionary (Wade 1998) but subsequently recovery factor values of 0.1 and 1 have been suggested for endangered marine mammals and fish bycatch, respectively (Taylor et al. 2003, Zhou et al. 2011). Recent research has proposed extending PBR to account for indirect effects such as the reduction of food supplies (Moore 2013) and population age/size structure (Curtis and Moore 2013). The main limitation with regard to the application of PBR to elasmobranchs is the absence of a population estimate for most species (see Robards et al. 2009 for a similar point regarding marine mammals). Even for an elasmobranch like the whale shark, for which PBR could be calculated from observer records (SPC-OFP 2012), recent research has been limited to patterns and trends in abundance rather than population estimates (Sequiera et al. 2013a, b).

5.3. Potential Application to WCPFC Elasmobranchs

Life history parameters from the literature were used to calculate the three risk-based LRPs using six formulae

To explore the application of risk-based LRPs to WCPFC elasmobranchs, the methods in Zhou et al. (2011) were used to calculate F_{msm}, F_{lim} and F_{crash} LRPs for eleven of the WCPFC key shark species. Given the preference expressed by Zhou et al. (2011) for calculations based on reliable estimates of r (Method 1), this subset of species was selected to include only those species for which such estimates were available[16]. For each of the eleven species, medians and confidence intervals for the intrinsic rate of increase, r, were taken from Cortés et al. (2010), except for pelagic thresher which was taken from Cortés et al. (2002), and applied in Method 1. All other parameters (Methods 2-6) were taken from Fishbase (2014) as follows:

- M: Fishbase Life History Tool page "natural mortality", standard error range

[15] Optimum sustainable level is defined as a probability of at least 95% that populations at carrying capacity (or B_{MSY}, Moore et al. 2013) maintain that level for at least 20 years and that populations starting at 30% of carrying-capacity recovered to carrying capacity within 100 years (Wade 1998).

[16] Data were considered inadequate to support calculations for the other three WCPFC key shark species: great hammerhead, winghead and whale shark.

- L_∞: Fishbase Life History Tool page "Linf" (calculated), point estimate
- K: Fishbase Growth Parameters page "K", all listed point estimates that are not marked "questionable", or if none, from calculated value on the Life History Tool page
- T: Fishbase Growth Parameters page "T", all listed point estimates that are not marked "questionable" or if none, from Life History Tool page
- t_m: Fishbase Age/Size page (List of Population Characteristics) "Tmax", all listed point estimated that are not marked "questionable" or if none, from Life History Tool page
- t_{mat}: Fishbase Maturity Data page all listed point estimates (if available) or Life History Tool page, "Age at First Maturity", calculated point estimate

The calculations were implemented in a probabilistic manner in an attempt to incorporate uncertainty

A WinBUGS model[17] was used to calculate the LRPs for each species (Annex A). Methods 1 and 2 were implemented by using the range of values in the literature as endpoints for uniform distributions for r and M, respectively. For Methods 2-6, ω was implemented as a normal distribution with a mean of 0.41 and precision of 123.45 (equivalent to a standard deviation of 0.09; Zhou et al. (2012)). L_∞ was implemented as a point estimate as there was only one value available per species in Fishbase (2014). All of the other variables were assigned semi-informative prior distributions across all species as follows:

- K was assumed to range from 0.05 and 0.5 (Pardo et al. 2013);
- T was assumed to range from 7 to 30 degrees C;
- t_m was assumed to range from 8 to 40 years; and
- t_{mat} was assumed to range from 4 to 20 years.

Each of these four parameters was then updated with the data available from Fishbase (2014) for each species individually to form species-specific posterior distributions which were then used in the calculations shown in Table 4. Generally the number of data points available to update the prior was small (often n=1) and was never greater than 19. The model was run for 10,000 iterations (burn in) and then monitored for a subsequent 5,000 iterations to produce the results are shown in Figure 3 and Annex B.

The calculations based on the intrinsic rate of increase were the simplest and generally most conservative

Given the preliminary nature of this analysis, the results from the six methods are presented separately rather than combined with equal (per Zhou et al. 2011) or other weights. Often Method 1, the method based on r and recommended by Zhou et al. (2011) produced the lowest (most conservative) LRP benchmarks. In some cases these benchmarks were extremely small, or in the case of bigeye thresher sharks less than zero, reflecting the negative r value at the bottom of the range for that species (Cortés et al. 2010). For most species, Methods 4, 5 and 6 produced the highest and most variable LRP benchmarks. Despite having the greatest number of parameters, Method 3's results were usually not the most variable and in many cases were similar to those from Method 2, perhaps reflecting the fact that the natural mortality value used in Method 2 may have been calculated from the same parameters used in Method 3. Further

[17] Documentation and software available at http://www.mrc-bsu.cam.ac.uk/software/bugs/

consideration should be given to which methods are most credible and the best algorithm for combining their results into a single LRP for each species.

Current fishing mortality estimates for oceanic whitetip and silky sharks exceed almost of all the F_{crash} confidence intervals

Although these calculated LRP benchmarks are merely indicative, and the input data should be thoroughly vetted by species experts before using them, it is interesting to note that the results for F_{crash} under Method 1 are similar to the F_{MSY} estimates produced by stock assessments for oceanic whitetip and silky sharks by Rice & Harley (2012, 2013). The risk-based F_{crash} and the estimated F_{MSY} were 0.10 and 0.07, respectively, for oceanic whitetip shark, and 0.06 and 0.08, respectively for silky shark[18]. The Rice & Harley (2012, 2013) estimates of current fishing mortality can also be compared to F_{crash} values for illustration purposes. Rice & Harley (2012) estimated current (2005-2008) F for oceanic whitetip sharks at 0.469 which exceeds the F_{crash} LRP benchmark's 95% confidence interval for all methods except Method 5. The estimated current (2005-2008) F for silky sharks was slightly lower at 0.374 (Rice & Harley 2012) but again this exceeds the F_{crash} LRP benchmark's 95% confidence interval for all methods except Method 5. The situation for both species would thus be classified by Zhou et al. (2011) as "extremely high risk".

[18] Ideally the confidence intervals, rather than the medians, for each estimate should be compared to determine whether a statistically significant difference exists. However, confidence intervals for F_{MSY} and $F_{current}$ were not presented in Rice and Harley (2012, 2013).

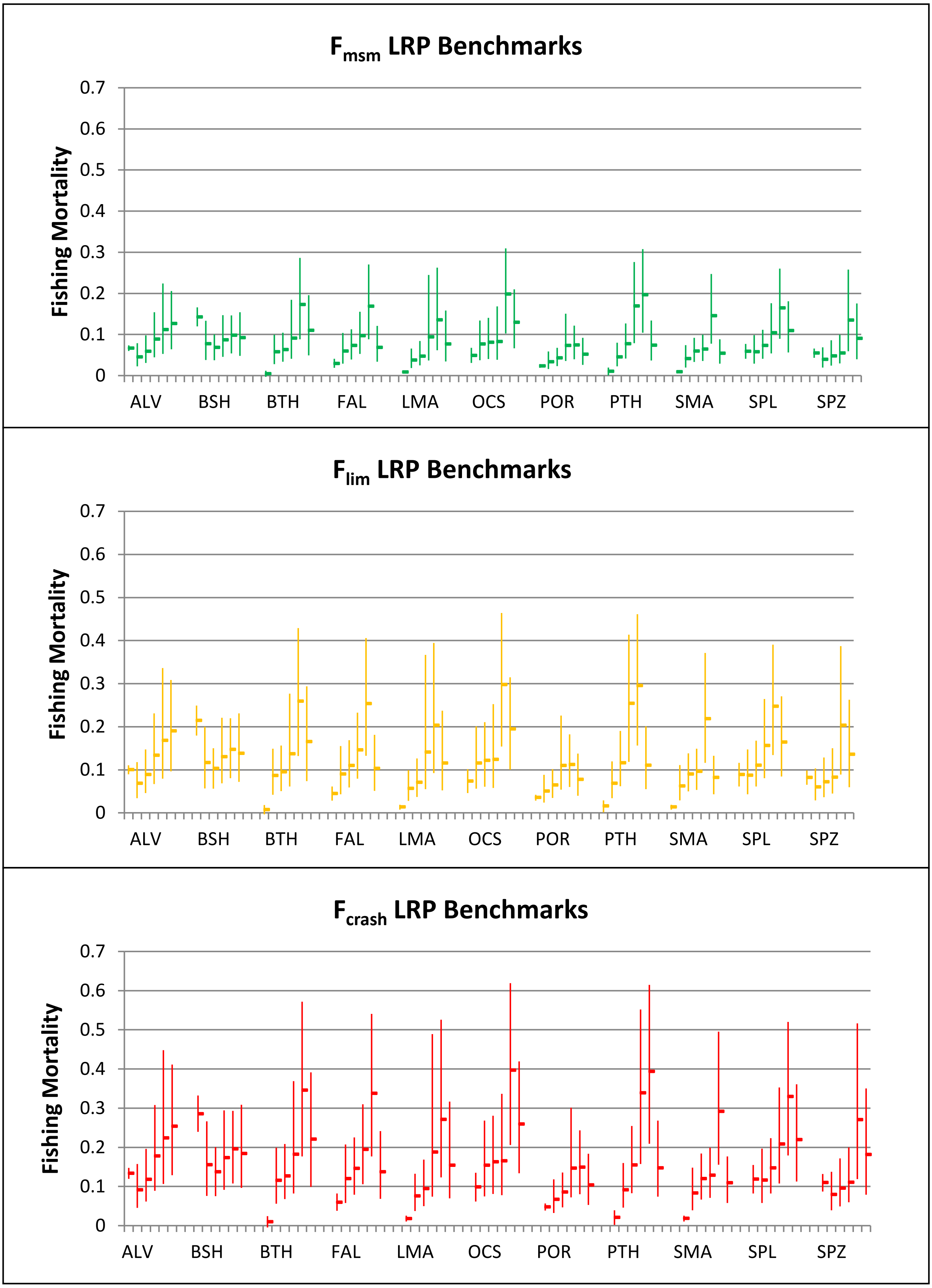

Figure 3. Probabilistic calculation of F_{msm}, F_{lim} and F_{crash} LRPs *sensu* Zhou et al. (2011) and data from Cortés et al. (2010), Cortés (2002) and Fishbase (2014). Shark species are abbreviated as ALV=common thresher, BSH=blue, BTH=bigeye thresher, FAL=silky, LMA=longfin mako, OCS=oceanic whitetip, POR=porbeagle, PTH=pelagic thresher, SMA=shortfin mako, SPL=scalloped hammerhead, and SPZ=smooth hammerhead.

6. Conclusions and Recommendations

6.1. Conclusions

The tiered, pressure-stock paired LRP approach adopted for WCPFC target stocks is also appropriate for elasmobranchs

The objective of this paper was to recommend appropriate LRPs for WCPFC elasmobranchs taking into consideration the WCPFC's LRP framework for target species. The paired (i.e. pressure and state) and tiered (i.e. based on availability of information) characteristics of that framework are equally useful for elasmobranchs and should be maintained for consistency. However, the target species framework presumes that a stock assessment will be available for each species and this will not necessarily be the case for all WCPFC key shark species. Therefore rather than constraining the elasmobranch LRPs to estimated LRPs only, this review considered estimated, empirical and risk-based LRPs.

Calculations of LRPs in this paper should be considered as indicative only

A summary of the LRPs considered in this paper and their advantages and disadvantages is shown in Table 5. This table also compiles LRP values from the existing WCPFC stock assessments, and in some cases indicative calculations made in this study, for the two shark species thus far assessed by the WCPFC (i.e. oceanic whitetip and silky sharks). As these values are in some cases for illustration only they should not be considered the actual proposed values of the LRPs. For some missing cases (i.e. NA in the table), values could be derived from existing information (e.g. by re-formatting the output of the stock assessment models and re-running them) but it was beyond the scope of this study to do so.

Table 5. Advantages and disadvantages of LRPs for elasmobranchs considered in this paper. General comments by type of LRP are shown in grey; comments on specific LRPs are shown below each heading. Indicative values are shown for specific LRPs only.

LRP	**Advantages**	**Disadvantages**	**Indicative Value for Oceanic Whitetip Shark**	**Indicative Value for Silky Shark**
Estimated LRPs	- Maximum use of information - Consistent with LRP framework for WCPFC tunas	- Require population models (resource and data intensive)		
$F_{current}/F_{MSY}=1$	- Considered best practice when estimated with confidence - Widely used, and applied in elasmobranch management by the US and ICCAT	- Depends on SRR, so difficult to estimate robustly - Based on yield rather than conservation considerations - F_{MSY} is sensitive to changes in selectivity	6.5 (3-20)	4.48 (1.41-7.96)
$F_{current}/F_{x\%SPRunfished}=1$	- Easier to estimate than F_{MSY} - Widely used	- The appropriate value of X may be difficult to agree	NA	NA
$SB_{current}$ = *SB corresponding to* $R_{current}/R_{F=0}$ = 0.5	- A simplified approach assuming that an LRP benchmark is a reduction in recruitment of 50% - Based on conservation considerations	- Depends on SRR, so difficult to estimate robustly - Will require further consideration and testing, particularly with reference to sharks	0.065 <<0.265	NA
$SB_{current}/SB_{MSY}=1$	- Applied in elasmobranch management by the US and Australia - Could factor B_{MSY} by natural mortality	- Depends on SRR so difficult to estimate robustly - Based on yield rather than conservation considerations - B_{MSY} is sensitive to changes in selectivity	0.153 (0.082-0.409)	0.70 (0.51-1.23)
$SB_{current}/x\%\ SB_{unfished}$ *(virgin or dynamic)*	- Based on conservation considerations - Consistent with LRP framework for WCPFC tunas - Depletion level can be set conservatively (i.e. 30%)	- Need precise definition of unfished conditions	$SB_{current}/SB_{virgin}$ = 0.065 $SB_{current}/SB_{dynamic\ unfished}$ = NA	$SB_{current}/SB_{virgin}$ = 0.272 $SB_{current}/SB_{dynamic\ unfished}$ = NA

LRP	Advantages	Disadvantages	Indicative Value for Oceanic Whitetip Shark	Indicative Value for Silky Shark
Other proxies for biomass-based LRPs	- May provide various advantages over the widely used LRPs above	- In various early stages of development and require further testing	NA	NA
Empirical LRPs	- Indicators can be directly measured in the field - Once developed a stock assessment model is not required - Can be more transparent and direct	- Difficult to develop and test appropriately; not widely used - Requires a stock assessment and an agreed estimated LRP as a starting point		
Catch rate	- Potentially sensitive to abundance change - Showed reasonable, but not high, contrast in an application to WCPFC oceanic whitetip - Identified as promising for sharks by IATTC	- Catch rates require appropriate standardization - May be insensitive in species with low catch rates or with data quality issues such as species identification	NA	NA
Length (mean / 95th percentile)	- Can be indicative of fishing mortality	- Indicators may have low sensitivity in elasmobranch fisheries - Indicators affected by selectivity change and recruitment variation	NA	NA
Weight (mean / 95th percentile)	- Can be indicative of fishing mortality	- Indicators may have low sensitivity in elasmobranch fisheries - Indicators affected by selectivity change and recruitment variation	NA	NA

LRP	Advantages	Disadvantages	Indicative Value for Oceanic Whitetip Shark	Indicative Value for Silky Shark
Risk-based LRPs	- Simple to calculate if reliable life history parameters are available - Can be combined/contrasted with estimated LRPs - Used in Australian fisheries management	- Focused only on 'pressure' (F), not 'state' (B) - May be overly reliant on difficult-to-estimate life history parameters - May be oversimplified with regard to selectivity, density dependence, etc.		
F_{msm}	- Represents the instantaneous F that corresponds to the maximum number of fish that can be killed by fishing in the long term (indicates overfishing)	- See Risk LRPs above	Means for methods 1-6 range from 0.05 – 0.20; stock assessment estimates $F_{current}$ at 0.469	- Means for methods 1-6 range from 0.03 – 0.17; stock assessment estimates $F_{current}$ at 0.374
F_{lim}	- Represents the instantaneous F that corresponds to the limit biomass assumed to be half the biomass that supports a maximum sustainable fishing mortality (indicates high risk)	- See Risk LRPs above	Means for methods 1-6 range from 0.07 – 0.30; stock assessment estimates $F_{current}$ at 0.469	- Means for methods 1-6 range from 0.04 – 0.25; stock assessment estimates $F_{current}$ at 0.374
F_{crash}	- The minimum unsustainable instantaneous F that will lead to population extinction in the long term (indicates extremely high risk)	- See Risk LRPs above	- Means for methods 1-6 range from 0.10 – 0.40; stock assessment estimates $F_{current}$ at 0.469	- Means for methods 1-6 range from 0.06 – 0.34; stock assessment estimates $F_{current}$ at 0.374

6.2. Recommendations

$F_{current}/F_{MSY}$ is recommended as an LRP when there is confidence that the SRR is well-known; if not, an $F_{60\%SPRunfished}$ LRP may be presented as an alternative by the assessors and considered by the WCPFC SC

For those elasmobranchs evaluated using a stock assessment model for which there is confidence that the stock-recruitment relationship is appropriately specified, the best practice fishing pressure LRP appears to be F_{MSY} (see Section 3). Although it has been argued that the concept of F_{MSY} is based on yield, not population sustainability, this LRP would be appropriately precautionary for non-target stocks. F_{MSY} is applied as a benchmark by ICCAT and the United States in elasmobranch stock assessments, and is under consideration by the WCPFC as an LRP for target species. In cases where the stock-recruitment relationship is highly uncertain, it is recommended that the assessors also compare $F_{current}$ to an SPR-based LRP such as $F_{60\%SPR,unfished}$, and discuss which LRP is most appropriate. The selected LRP should then be considered by the WCPFC Scientific Committee (SC) when the assessment is presented. If the WCPFC SC is not confident in either the F_{MSY} or $F_{60\%SPRunfished}$ LRP, a risk-based LRP may be used (see below).

If no stock assessment is available, risk-based fishing mortality LRPs are recommended

For those elasmobranchs which have not been evaluated using a stock assessment model, it is recommended that an estimate of current fishing mortality (F) be developed using catch curves, productivity-susceptibility analysis, or other suitable means. Risk-based LRPs in the form of F_{msm}, F_{lim} and F_{crash} as proposed by Zhou et al. (2011) should then be used to evaluate the current fishing mortality, with F_{msm} recommended as the most appropriate benchmark to determine overfishing (see Section 5). These LRPs can be developed for all WCPFC key shark species, although it should be noted that data will be sparse and/or uncertain for some species, and specification of appropriate values may require expert judgment. A working group of elasmobranch experts should be convened to identify and evaluate the appropriate life history data to be used in the calculation of the risk-based LRPs for the WCPFC key shark species.

A biomass LRP in the form of $SB_{current}/X\%SB_{dyanmic,unfished}$ is recommended for application to elasmobranchs with stock assessments ($SB_{current}/30\%SB_{dyanmic,unfished}$ is suggested as precautionary)

Elasmobranchs with stock assessments can also be evaluated using a biomass-based LRP. Consistent with the adopted WCPFC LRPs for target species, i.e. $SB_{current}/20\%SB_{dyanmic10,unfished}$, a biomass-depletion LRP is recommended for WCPFC elasmobranchs (see Section 3). However, instead of allowing depletion to 20% of the biomass expected to be present in the recent period in the absence of fishing and under current (10 year) environmental conditions, a level of 30% is proposed as a more precautionary level for elasmobranchs due to their lower productivity. Formulation of the LRP relative to dynamic, unfished biomass avoids issues associated with the expected fluctuation in B_{MSY} due to environmental conditions. Unfortunately, no risk-based approach to biomass-based LRPs has been developed, therefore no biomass-based LRP is proposed for elasmobranchs without stock assessments.

Other LRPs cannot be recommended at this time but may develop in the coming years

Other potential LRPs based on SPR, reduction of recruitment or empirical measures (e.g. catch rate or length values designed to signal unacceptable population states) cannot be proposed at this time. Further development of reduction of recruitment estimated LRPs and catch rate empirical LRPs, including application to shark species, is anticipated from IATTC in the coming years. These developments should be monitored closely in order to determine whether a compatible approach would have merit for the WCPFC.

A summary of the recommended LRPs for WCPFC elasmobranchs is presented in Table 6. Level 1 LRPs are intended to apply to all elasmobranchs for which stock assessment/population dynamics models are available. The Level 2 LRP would apply to all other WCPFC key shark species.

Table 6. LRPs recommended in this paper for WCPFC elasmobranchs.

Level	Fishing Mortality LRP	Biomass LRP	Species
1	$F_{current}/F_{MSY}$ or, if estimates premised on the SRR are not considered reliable, $F_{60\%SPRunfished}$ (to be determined on a case by case basis)	$SB_{current}/30\%SB_{dyanmic,unfished}$	Species with adopted stock assessments (currently oceanic whitetip and silky shark)
2	$F_{current}/F_{msm}$ (risk-based)		All other WCPFC key shark species

The outlook for conducting stock assessments of all WCPFC key shark species should be confirmed

WCPFC stock assessments have been undertaken and adopted for oceanic whitetip and silky sharks, and are in progress for blue sharks, but the outlook for further key shark species stock assessments is unclear. It is recommended that the WCPFC SC task the WCPFC Scientific Services Provider to determine, for each WCPFC key shark species, whether the existing data are sufficient to support a stock assessment, and if not, to identify the critical data gaps. For those species that can support stock assessments, future stock assessments should provide estimates (with confidence intervals) for $F_{current}$, F_{MSY}, $F_{60\%SPRunfished}$, $SB_{current}$ and $SB_{dynamic10,unfished}$ to facilitate comparison to the recommended LRPs.

An expert panel should be convened to refine the data inputs for risk-based LRPs

A priority issue for implementation of a risk-based approach for all other WCPFC key shark species is to convene an expert panel to identify the most appropriate life history data to be used in calculating the risk-based LRPs. Recommendations may take the form of a single estimate, range or distribution for each parameter, or of an approved dataset to be used in a probabilistic approach as demonstrated in this paper. It is also recommended that trial development of catch curve and productivity-susceptibility based estimates of fishing mortality be undertaken to explore how these estimates can be used in lieu of stock assessment-based *F* estimates when comparing to risk-based LRPs. Any critical data gaps hampering these types of estimates should be highlighted.

LRPs must be implemented within a comprehensive management scheme in order to be effective

Finally, as noted by Caddy (1998) reference points per se do not ensure responsible or precautionary management; they can only be effective if management responses are pre-negotiated and appropriately implemented. Development of LRPs in this paper should thus be seen as merely one element of a comprehensive conservation and management plan for WCPFC elasmobranchs. Other elements including development of appropriate assessment methodologies, effective mitigation measures, improved fisheries monitoring, and pre-agreed harvest control rules should progress in parallel with further work on LRPs. Work on all of these fronts will be necessary to reverse the depleted state of some WCPFC elasmobranch populations and to ensure that the elasmobranch mortality rates associated with WCPFC tuna fisheries are sustainable.

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APPENDIX A. WinBUGS model for probabilistic calculation of risk-based LRPs sensu Zhou et al. (2011)

```
model
{
#METHOD 1:  takes "r" (intrinsic rate of increase) (take the ln of lambda to get r)
for (i in 1:11)                 # elevenspecies OCS, FAL, BSH, SMA, LMA, BTH, ALV, POR, SPL, SPZ, PTH
                {
                        r[i]~ dunif(Cortes_r[i,1],Cortes_r[i,2])
                        Fmsm1[i] <- 0.5*r[i]
                        Flim1[i] <- 0.75*r[i]
                        Fcrash1[i] <- r[i]
                }

omega ~ dnorm(0.41,123.45)

#METHOD 2: omega * M (as given in Fishbase)
                for (i in 1:11) {
                        M2[i] ~ dunif(FishbaseM[i,1],FishbaseM[i,2])
                        Fmsm2[i] <- omega * M2[i]
                        Flim2[i] <- 1.5 * omega * M2[i]
                        Fcrash2[i] <- 2 * omega * M2[i]
                        }

#METHOD 3:  omega * M (as calculated from basic parameters in Fishbase)

#first get Linf, k and T for each species
#Linf can be gotten from Fishbase
#use an informative prior from Pardo et al. (2013) and data for each species to get K

for (i in 1:11)
        {
                priorK[i]~ dunif(-2.995,-0.693)         #from Pardo et al. 2013, k ranges from 0.05 to 0.5 (Fig 2b)
        for (j in 1:19)
                        {
                        Kdata[i,j] ~ dlnorm(priorK[i],10)         #if this is run w/o data the range is -2.938 to -0.7535
(0.05 to 0.47) -- an inf. prior
                        }
                K[i] <- exp(priorK[i])                          #this is K after updating with the available data
                }

#now get T (in the same way)

for (i in 1:11)
        {
                priorT[i]~ dunif(1.946,3.401)           #assume temperature varies from 7 to 30 C
                for (j in 1:19)
                        {
                        Tdata[i,j] ~ dlnorm(priorT[i],10)#gives a range of 7 to 29C
                        }
                T[i] <- exp(priorT[i])                          #this is T after updating with the available data
                }

#now calculate M
                        for (i in 1:11) {
                        M3[i] <- exp(-0.0152 - (0.279*log(Linf[i])) + (0.6543*log(K[i])) + (0.4634*log(T[i])))
                        Fmsm3[i] <- omega * M3[i]
                        Flim3[i] <- 1.5 * omega * M3[i]
                        Fcrash3[i] <- 2 * omega * M3[i]
                        }

#METHOD 4:  omega * M (as calculated based on maximum reproductive age (tm))

for (i in 1:11)
        {
                priorTM[i]~ dunif(2.079,3.738)          #assume max age varies from 8 to 42
                for (j in 1:19)
                        {
                        TMdata[i,j] ~ dlnorm(priorTM[i],10)       #gives a range of 8 to 40
                        }
                TM[i] <- exp(priorTM[i])                #this is TM after updating with the available data
                }
```

```
#now calculate M
					for (i in 1:11) {
			M4[i] <- exp(1.44 - (0.982*log(TM[i])))
			Fmsm4[i] <- omega * M4[i]
			Flim4[i] <- 1.5 * omega * M4[i]
			Fcrash4[i] <- 2 * omega * M4[i]
			}

#METHOD 5:  omega * M (as calculated based on Linf and T)

		for (i in 1:11) {
			M5[i] <- pow(10,0.566-(0.718*log(Linf[i]))) + (0.02*T[i])
			Fmsm5[i] <- omega * M5[i]
			Flim5[i] <- 1.5 * omega * M5[i]
			Fcrash5[i] <- 2 * omega * M5[i]
			}

#METHOD 6:   omega * M (calculated based on age at maturation, tmat)

for (i in 1:11)
	{
		priorTmat[i]~ dunif(1.386,2.996)			#assume age at maturity varies from 4 to 20
		for (j in 1:19)
			{
			Tmatdata[i,j] ~ dlnorm(priorTmat[i],10)	#gives a range of 4 to 19
			}
		Tmat[i] <- exp(priorTmat[i])				#this is TM after updating with the available
data
		}

#now calculate M
					for (i in 1:11) {
			M6[i] <- 1.65/Tmat[i]
			Fmsm6[i] <- omega * M6[i]
			Flim6[i] <- 1.5 * omega * M6[i]
			Fcrash6[i] <- 2 * omega * M6[i]
			}

}	#end of model


#DATA
list(
Cortes_r = structure(.Data = c(			#all from Cortes et al. 2010, except PTH from Cortes 2002
0.060,0.137,				#OCS (Low, High)
0.037,0.083,			#FAL
0.237,0.334,			#BSH
0.010,0.026,			#SMA
0.010,0.026,			#LMA
-0.006,0.025,			#BTH
0.119,0.148,			#ALV
0.038,0.057,			#POR
0.080,0.157,			#SPL
0.086,0.133,			#SPZ
0.0009995,0.0402		#PTH
), .Dim=c(11,2)),

FishbaseM = structure(.Data = c(
0.12,0.27,		#OCS (Low, High)
0.09,0.21,		#FAL
0.12,0.27,		#BSH
0.06,0.15,		#SMA
0.06,0.13,		#LMA
0.09,0.20,		#BTH
0.07,0.16,		#ALV
0.05,0.12,		#POR
0.09,0.20,		#SPL
0.06,0.14,		#SPZ
0.07,0.16		#PTH
), .Dim=c(11,2)),

Linf = c(350,315,304,348,419,422,651,349,329,501,350),

Kdata = structure(.Data = c(
0.11,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
```

```
0.19,0.15,0.10,0.08,0.09,0.05,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.25,0.14,0.13,0.11,0.13,0.18,0.16,0.14,0.16,0.09,0.10,0.16,0.10,0.15,0.16,0.12,0.07,0.13,0.11,
0.11,0.27,0.05,0.07,0.05,0.07,0.20,0.04,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.06,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.09,0.09,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.19,0.12,0.10,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.08,0.12,0.06,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.11,0.09,0.25,0.22,0.07,0.07,0.05,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.07,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
0.12,0.09,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA
), .Dim=c(11,19)),

Tdata = structure(.Data = c(
27.5,27.0,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
21,21,21,20,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
14,12,14,12,12,12,12,12,12,12,12,9,NA,NA,NA,NA,NA,NA,NA,
20.5,14,20.5,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
17,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
22,22,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
14,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
10,7,10,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
15,15,22,22,26,25,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
17,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
28.5,20,29,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA
), .Dim=c(11,19)),

TMdata = structure(.Data = c(
22,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
13,14,23,21,25,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
19.7,22.8, 20,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
20.6,30.6,29,29,32,28,31,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
20,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
19,22,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
25,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
10.6,35,14,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
42,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
9,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA
), .Dim=c(11,19)),

Tmatdata = structure(.Data = c(
4,5.8,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
8,12,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
8,8,6,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
8,8,18,20,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
8.6,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
5.7,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
4.8,5.3,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
10,17,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
3.8,4,15,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
7.2,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,
7.4,11,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA,NA
), .Dim=c(11,19)))
```

APPENDIX B. Results from WinBUGS model for probabilistic calculation of risk-based LRPs sensu Zhou et al. (2011)

Method	LRP	species	mean	sd	MC error	2.50%	median	97.50%
1	Fcrash	ALV	0.1334	0.008369	1.25E-04	0.1197	0.1334	0.1472
2	Fcrash	ALV	0.094	0.02977	4.76E-04	0.04541	0.09132	0.1576
3	Fcrash	ALV	0.1207	0.03457	5.19E-04	0.0616	0.1181	0.1962
4	Fcrash	ALV	0.183	0.05641	7.84E-04	0.08903	0.1777	0.308
5	Fcrash	ALV	0.238	0.08849	0.0013	0.1061	0.2238	0.448
6	Fcrash	ALV	0.2572	0.07201	0.001128	0.1288	0.2535	0.411
1	Fcrash	BSH	0.2853	0.02821	4.06E-04	0.2395	0.2854	0.332
2	Fcrash	BSH	0.1598	0.05077	7.76E-04	0.0756	0.155	0.2664
3	Fcrash	BSH	0.1373	0.03137	4.75E-04	0.07513	0.137	0.2003
4	Fcrash	BSH	0.1786	0.05144	7.51E-04	0.09127	0.1734	0.2941
5	Fcrash	BSH	0.1976	0.0469	7.11E-04	0.1077	0.1959	0.293
6	Fcrash	BSH	0.1884	0.05337	8.34E-04	0.09613	0.184	0.3084
1	Fcrash	BTH	0.009551	0.009028	1.16E-04	-0.00529	0.009668	0.02421
2	Fcrash	BTH	0.1193	0.03772	6.04E-04	0.05609	0.1157	0.1988
3	Fcrash	BTH	0.1293	0.03609	5.34E-04	0.06776	0.1265	0.2085
4	Fcrash	BTH	0.193	0.07318	0.001044	0.08193	0.1822	0.3689
5	Fcrash	BTH	0.355	0.1016	0.001464	0.1765	0.3458	0.5721
6	Fcrash	BTH	0.227	0.07518	0.001078	0.0987	0.2206	0.3916
1	Fcrash	FAL	0.05969	0.01322	1.89E-04	0.03806	0.0595	0.08188
2	Fcrash	FAL	0.1234	0.0395	5.01E-04	0.05788	0.1196	0.2072
3	Fcrash	FAL	0.1479	0.03663	5.69E-04	0.07879	0.1461	0.225
4	Fcrash	FAL	0.198	0.05179	7.71E-04	0.1056	0.1945	0.3101
5	Fcrash	FAL	0.3442	0.09247	0.001432	0.1767	0.3378	0.5409
6	Fcrash	FAL	0.1414	0.04434	6.78E-04	0.0683	0.137	0.2416
1	Fcrash	LMA	0.01791	0.004652	7.07E-05	0.01041	0.01788	0.02562
2	Fcrash	LMA	0.07789	0.02437	3.44E-04	0.03744	0.07544	0.1323
3	Fcrash	LMA	0.098	0.02984	3.75E-04	0.04948	0.09448	0.1687
4	Fcrash	LMA	0.2179	0.1145	0.001679	0.07387	0.1876	0.4892
5	Fcrash	LMA	0.2838	0.1025	0.001369	0.1232	0.271	0.5259
6	Fcrash	LMA	0.1642	0.06314	7.87E-04	0.06948	0.1541	0.3165
1	Fcrash	OCS	0.09825	0.02232	2.89E-04	0.0617	0.09838	0.1351
2	Fcrash	OCS	0.1595	0.05058	7.60E-04	0.07474	0.1541	0.2684
3	Fcrash	OCS	0.167	0.05125	7.77E-04	0.08103	0.1624	0.2808
4	Fcrash	OCS	0.176	0.06741	9.12E-04	0.07754	0.1652	0.3364
5	Fcrash	OCS	0.3999	0.1055	0.001517	0.2058	0.3967	0.6191
6	Fcrash	OCS	0.2636	0.0724	9.42E-04	0.1336	0.2591	0.4196
1	Fcrash	POR	0.04738	0.005448	7.58E-05	0.03843	0.04737	0.0565
2	Fcrash	POR	0.06963	0.02288	3.54E-04	0.0323	0.06713	0.118
3	Fcrash	POR	0.08714	0.02275	3.48E-04	0.04645	0.08565	0.1354
4	Fcrash	POR	0.1571	0.05923	9.61E-04	0.07189	0.1464	0.3011
5	Fcrash	POR	0.1526	0.04187	5.56E-04	0.08024	0.1492	0.2431
6	Fcrash	POR	0.1076	0.0333	4.92E-04	0.05291	0.1035	0.1834
1	Fcrash	PTH	0.02064	0.01122	1.52E-04	0.001947	0.02085	0.03911
2	Fcrash	PTH	0.09461	0.0304	4.35E-04	0.04585	0.09114	0.1598
3	Fcrash	PTH	0.1588	0.04398	5.51E-04	0.08274	0.1548	0.2542
4	Fcrash	PTH	0.3423	0.1018	0.001524	0.1577	0.3387	0.5521
5	Fcrash	PTH	0.398	0.104	0.001422	0.2088	0.3936	0.6147
6	Fcrash	PTH	0.1537	0.04955	7.26E-04	0.07385	0.1473	0.2683
1	Fcrash	SMA	0.01802	0.0046	7.05E-05	0.0104	0.01813	0.02562
2	Fcrash	SMA	0.08602	0.02906	4.72E-04	0.03893	0.08309	0.1479
3	Fcrash	SMA	0.1213	0.0297	4.43E-04	0.0668	0.1196	0.1841
4	Fcrash	SMA	0.1304	0.03264	4.72E-04	0.07106	0.1286	0.1989
5	Fcrash	SMA	0.2996	0.08557	0.001281	0.1553	0.2915	0.495
6	Fcrash	SMA	0.1111	0.02989	4.44E-04	0.05797	0.1093	0.177
1	Fcrash	SPL	0.1184	0.02221	2.75E-04	0.08189	0.1187	0.1549
2	Fcrash	SPL	0.1188	0.03672	5.90E-04	0.05777	0.1162	0.1968
3	Fcrash	SPL	0.1479	0.03567	5.20E-04	0.08189	0.1469	0.2234
4	Fcrash	SPL	0.2137	0.06184	0.001035	0.1078	0.2081	0.3528
5	Fcrash	SPL	0.3356	0.0858	0.001221	0.1793	0.3297	0.5204
6	Fcrash	SPL	0.2243	0.06278	9.85E-04	0.1127	0.2191	0.3611
1	Fcrash	SPZ	0.1094	0.01349	1.66E-04	0.08735	0.1095	0.132
2	Fcrash	SPZ	0.08214	0.02657	4.33E-04	0.03899	0.07956	0.1378
3	Fcrash	SPZ	0.09974	0.03146	5.02E-04	0.04885	0.09577	0.1717
4	Fcrash	SPZ	0.1151	0.03485	5.51E-04	0.05996	0.1102	0.1998
5	Fcrash	SPZ	0.2835	0.1025	0.001628	0.1187	0.2704	0.5162
6	Fcrash	SPZ	0.1906	0.07	0.001167	0.07926	0.1812	0.3505

Method	LRP	species	mean	sd	MC error	2.50%	median	97.50%
1	Flim	ALV	0.1	0.006277	9.40E-05	0.08977	0.1001	0.1104
2	Flim	ALV	0.0705	0.02233	3.57E-04	0.03406	0.06849	0.1182
3	Flim	ALV	0.09053	0.02593	3.89E-04	0.0462	0.08855	0.1471
4	Flim	ALV	0.1373	0.04231	5.88E-04	0.06677	0.1333	0.231
5	Flim	ALV	0.1785	0.06637	9.75E-04	0.07959	0.1679	0.336
6	Flim	ALV	0.1929	0.05401	8.46E-04	0.09659	0.1901	0.3083
1	Flim	BSH	0.214	0.02116	3.05E-04	0.1796	0.2141	0.249
2	Flim	BSH	0.1198	0.03808	5.82E-04	0.0567	0.1163	0.1998
3	Flim	BSH	0.103	0.02353	3.56E-04	0.05635	0.1028	0.1502
4	Flim	BSH	0.134	0.03858	5.63E-04	0.06845	0.1301	0.2206
5	Flim	BSH	0.1482	0.03517	5.33E-04	0.08078	0.1469	0.2198
6	Flim	BSH	0.1413	0.04003	6.26E-04	0.0721	0.138	0.2313
1	Flim	BTH	0.007163	0.006771	8.70E-05	-0.00397	0.007251	0.01816
2	Flim	BTH	0.08949	0.02829	4.53E-04	0.04206	0.08681	0.1491
3	Flim	BTH	0.09697	0.02706	4.01E-04	0.05082	0.09485	0.1564
4	Flim	BTH	0.1447	0.05488	7.83E-04	0.06145	0.1366	0.2767
5	Flim	BTH	0.2662	0.07621	0.001098	0.1323	0.2593	0.4291
6	Flim	BTH	0.1703	0.05638	8.09E-04	0.07403	0.1654	0.2937
1	Flim	FAL	0.04476	0.009915	1.41E-04	0.02854	0.04463	0.06141
2	Flim	FAL	0.09255	0.02963	3.76E-04	0.04341	0.08974	0.1554
3	Flim	FAL	0.1109	0.02747	4.27E-04	0.05909	0.1096	0.1688
4	Flim	FAL	0.1485	0.03884	5.79E-04	0.07923	0.1459	0.2326
5	Flim	FAL	0.2581	0.06936	0.001074	0.1326	0.2533	0.4057
6	Flim	FAL	0.106	0.03326	5.09E-04	0.05122	0.1028	0.1812
1	Flim	LMA	0.01344	0.003489	5.30E-05	0.00781	0.01341	0.01921
2	Flim	LMA	0.05842	0.01828	2.58E-04	0.02808	0.05658	0.09926
3	Flim	LMA	0.0735	0.02238	2.82E-04	0.03711	0.07086	0.1265
4	Flim	LMA	0.1634	0.08589	0.001259	0.0554	0.1407	0.3669
5	Flim	LMA	0.2128	0.07689	0.001027	0.09241	0.2032	0.3944
6	Flim	LMA	0.1232	0.04735	5.90E-04	0.05211	0.1156	0.2373
1	Flim	OCS	0.07368	0.01674	2.17E-04	0.04627	0.07378	0.1014
2	Flim	OCS	0.1197	0.03794	5.70E-04	0.05605	0.1156	0.2013
3	Flim	OCS	0.1252	0.03844	5.83E-04	0.06077	0.1218	0.2106
4	Flim	OCS	0.132	0.05056	6.84E-04	0.05816	0.1239	0.2523
5	Flim	OCS	0.2999	0.0791	0.001138	0.1543	0.2975	0.4643
6	Flim	OCS	0.1977	0.0543	7.07E-04	0.1002	0.1944	0.3147
1	Flim	POR	0.03554	0.004086	5.68E-05	0.02883	0.03553	0.04238
2	Flim	POR	0.05222	0.01716	2.66E-04	0.02422	0.05034	0.08847
3	Flim	POR	0.06535	0.01706	2.61E-04	0.03484	0.06424	0.1016
4	Flim	POR	0.1178	0.04442	7.21E-04	0.05392	0.1098	0.2259
5	Flim	POR	0.1144	0.0314	4.17E-04	0.06018	0.1119	0.1823
6	Flim	POR	0.08069	0.02497	3.69E-04	0.03968	0.07764	0.1376
1	Flim	PTH	0.01548	0.008418	1.14E-04	0.00146	0.01564	0.02933
2	Flim	PTH	0.07096	0.0228	3.26E-04	0.03439	0.06835	0.1199
3	Flim	PTH	0.1191	0.03298	4.13E-04	0.06205	0.1161	0.1906
4	Flim	PTH	0.2568	0.07638	0.001143	0.1183	0.254	0.414
5	Flim	PTH	0.2985	0.078	0.001067	0.1566	0.2952	0.461
6	Flim	PTH	0.1152	0.03716	5.44E-04	0.05538	0.1105	0.2012
1	Flim	SMA	0.01351	0.00345	5.29E-05	0.0078	0.0136	0.01921
2	Flim	SMA	0.06451	0.0218	3.54E-04	0.0292	0.06232	0.1109
3	Flim	SMA	0.09096	0.02227	3.32E-04	0.0501	0.0897	0.1381
4	Flim	SMA	0.0978	0.02448	3.54E-04	0.05329	0.09642	0.1492
5	Flim	SMA	0.2247	0.06418	9.61E-04	0.1165	0.2186	0.3712
6	Flim	SMA	0.08334	0.02242	3.33E-04	0.04348	0.08195	0.1327
1	Flim	SPL	0.08882	0.01665	2.06E-04	0.06142	0.08904	0.1162
2	Flim	SPL	0.08913	0.02754	4.42E-04	0.04332	0.08715	0.1476
3	Flim	SPL	0.111	0.02676	3.90E-04	0.06142	0.1102	0.1675
4	Flim	SPL	0.1602	0.04638	7.77E-04	0.08087	0.1561	0.2646
5	Flim	SPL	0.2517	0.06435	9.16E-04	0.1345	0.2472	0.3903
6	Flim	SPL	0.1682	0.04708	7.39E-04	0.08455	0.1643	0.2708
1	Flim	SPZ	0.08206	0.01012	1.24E-04	0.06551	0.08216	0.09897
2	Flim	SPZ	0.0616	0.01993	3.25E-04	0.02924	0.05967	0.1034
3	Flim	SPZ	0.07481	0.0236	3.77E-04	0.03664	0.07183	0.1288
4	Flim	SPZ	0.08633	0.02614	4.13E-04	0.04497	0.08265	0.1499
5	Flim	SPZ	0.2126	0.07687	0.001221	0.08902	0.2028	0.3871
6	Flim	SPZ	0.143	0.0525	8.75E-04	0.05944	0.1359	0.2629

Method	LRP	species	mean	sd	MC error	2.50%	median	97.50%
1	Fmsm	ALV	0.06669	0.004184	6.27E-05	0.05984	0.06671	0.0736
2	Fmsm	ALV	0.047	0.01488	2.38E-04	0.02271	0.04566	0.07882
3	Fmsm	ALV	0.06036	0.01728	2.60E-04	0.0308	0.05903	0.09809
4	Fmsm	ALV	0.09151	0.0282	3.92E-04	0.04451	0.08886	0.154
5	Fmsm	ALV	0.119	0.04425	6.50E-04	0.05306	0.1119	0.224
6	Fmsm	ALV	0.1286	0.036	5.64E-04	0.06439	0.1268	0.2055
1	Fmsm	BSH	0.1427	0.01411	2.03E-04	0.1197	0.1427	0.166
2	Fmsm	BSH	0.07989	0.02539	3.88E-04	0.0378	0.07752	0.1332
3	Fmsm	BSH	0.06867	0.01569	2.38E-04	0.03757	0.0685	0.1002
4	Fmsm	BSH	0.0893	0.02572	3.76E-04	0.04563	0.0867	0.1471
5	Fmsm	BSH	0.0988	0.02345	3.56E-04	0.05386	0.09795	0.1465
6	Fmsm	BSH	0.09421	0.02669	4.17E-04	0.04807	0.09201	0.1542
1	Fmsm	BTH	0.004775	0.004514	5.80E-05	-0.00264	0.004834	0.0121
2	Fmsm	BTH	0.05966	0.01886	3.02E-04	0.02804	0.05787	0.09942
3	Fmsm	BTH	0.06465	0.01804	2.67E-04	0.03388	0.06323	0.1042
4	Fmsm	BTH	0.09649	0.03659	5.22E-04	0.04096	0.09109	0.1845
5	Fmsm	BTH	0.1775	0.0508	7.32E-04	0.08823	0.1729	0.2861
6	Fmsm	BTH	0.1135	0.03759	5.39E-04	0.04935	0.1103	0.1958
1	Fmsm	FAL	0.02984	0.00661	9.43E-05	0.01903	0.02975	0.04094
2	Fmsm	FAL	0.0617	0.01975	2.51E-04	0.02894	0.05982	0.1036
3	Fmsm	FAL	0.07395	0.01832	2.84E-04	0.0394	0.07305	0.1125
4	Fmsm	FAL	0.099	0.0259	3.86E-04	0.05282	0.09727	0.1551
5	Fmsm	FAL	0.1721	0.04624	7.16E-04	0.08837	0.1689	0.2704
6	Fmsm	FAL	0.07068	0.02217	3.39E-04	0.03415	0.06851	0.1208
1	Fmsm	LMA	0.008957	0.002326	3.54E-05	0.005207	0.008941	0.01281
2	Fmsm	LMA	0.03895	0.01219	1.72E-04	0.01872	0.03772	0.06617
3	Fmsm	LMA	0.049	0.01492	1.88E-04	0.02474	0.04724	0.08434
4	Fmsm	LMA	0.109	0.05726	8.40E-04	0.03694	0.09378	0.2446
5	Fmsm	LMA	0.1419	0.05126	6.85E-04	0.06161	0.1355	0.2629
6	Fmsm	LMA	0.08211	0.03157	3.94E-04	0.03474	0.07704	0.1582
1	Fmsm	OCS	0.04912	0.01116	1.45E-04	0.03085	0.04919	0.06757
2	Fmsm	OCS	0.07977	0.02529	3.80E-04	0.03737	0.07706	0.1342
3	Fmsm	OCS	0.0835	0.02563	3.89E-04	0.04051	0.08119	0.1404
4	Fmsm	OCS	0.08801	0.03371	4.56E-04	0.03877	0.08262	0.1682
5	Fmsm	OCS	0.1999	0.05273	7.59E-04	0.1029	0.1984	0.3096
6	Fmsm	OCS	0.1318	0.0362	4.71E-04	0.0668	0.1296	0.2098
1	Fmsm	POR	0.02369	0.002724	3.79E-05	0.01922	0.02369	0.02825
2	Fmsm	POR	0.03482	0.01144	1.77E-04	0.01615	0.03356	0.05898
3	Fmsm	POR	0.04357	0.01137	1.74E-04	0.02323	0.04282	0.06772
4	Fmsm	POR	0.07854	0.02962	4.80E-04	0.03594	0.07321	0.1506
5	Fmsm	POR	0.07629	0.02093	2.78E-04	0.04012	0.07459	0.1216
6	Fmsm	POR	0.05379	0.01665	2.46E-04	0.02646	0.05176	0.09171
1	Fmsm	PTH	0.01032	0.005612	7.58E-05	9.73E-04	0.01043	0.01956
2	Fmsm	PTH	0.04731	0.0152	2.18E-04	0.02292	0.04557	0.07991
3	Fmsm	PTH	0.0794	0.02199	2.75E-04	0.04137	0.0774	0.1271
4	Fmsm	PTH	0.1712	0.05092	7.62E-04	0.07885	0.1693	0.276
5	Fmsm	PTH	0.199	0.052	7.11E-04	0.1044	0.1968	0.3074
6	Fmsm	PTH	0.07683	0.02477	3.63E-04	0.03692	0.07366	0.1341
1	Fmsm	SMA	0.00901	0.0023	3.53E-05	0.0052	0.009065	0.01281
2	Fmsm	SMA	0.04301	0.01453	2.36E-04	0.01946	0.04154	0.07393
3	Fmsm	SMA	0.06064	0.01485	2.21E-04	0.0334	0.0598	0.09205
4	Fmsm	SMA	0.0652	0.01632	2.36E-04	0.03553	0.06428	0.09944
5	Fmsm	SMA	0.1498	0.04279	6.41E-04	0.07765	0.1458	0.2475
6	Fmsm	SMA	0.05556	0.01494	2.22E-04	0.02899	0.05463	0.08849
1	Fmsm	SPL	0.05922	0.0111	1.37E-04	0.04094	0.05936	0.07744
2	Fmsm	SPL	0.05942	0.01836	2.95E-04	0.02888	0.0581	0.09839
3	Fmsm	SPL	0.07397	0.01784	2.60E-04	0.04095	0.07345	0.1117
4	Fmsm	SPL	0.1068	0.03092	5.18E-04	0.05391	0.1041	0.1764
5	Fmsm	SPL	0.1678	0.0429	6.11E-04	0.08967	0.1648	0.2602
6	Fmsm	SPL	0.1121	0.03139	4.93E-04	0.05637	0.1096	0.1806
1	Fmsm	SPZ	0.0547	0.006747	8.30E-05	0.04367	0.05477	0.06598
2	Fmsm	SPZ	0.04107	0.01328	2.17E-04	0.01949	0.03978	0.06891
3	Fmsm	SPZ	0.04987	0.01573	2.51E-04	0.02442	0.04789	0.08585
4	Fmsm	SPZ	0.05755	0.01742	2.75E-04	0.02998	0.0551	0.09992
5	Fmsm	SPZ	0.1417	0.05125	8.14E-04	0.05935	0.1352	0.2581
6	Fmsm	SPZ	0.09532	0.035	5.83E-04	0.03963	0.09061	0.1753