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Displaying uncertainty in the biological reference points of sharks

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ABSTRACT

Variability in life-history traits influences biological reference points (BRP). For data-poor species such as sharks, BRP have commonly been set at arbitrary values with little consideration of life-history variability. The temperate shark fisheries of Western Australia were used as a case study to develop species-specific limit, threshold and target BRP that consider life history uncertainty and population dynamics. Shark species with higher biological productivity had lower biomass BRP and higher fishing mortality BRP (F_{BRP}) than less productive species. The interplay of gear selectivity and variability in life history traits influenced BRP uncertainty, particularly for F_{BRP}. Traditionally, stock status is determined by comparing a stock-performance indicator (SPI) to a BRP point estimate based on a set probability of SPI exceeding the point BRP. We proposed an alternative approach where we considered distributions for both SPI and BRP and compared the proportion of overlap between those distributions. In practice, we consider this an improvement to characterizing both uncertainties and an easier-to-grasp concept than a probability of exceeding a point estimate.

1. Introduction

Ecologically sustainable development is a primary goal for fishery management. In practice, this high-level objective must be translated to an operational level where specific management actions are defined and their performance evaluated. In recent years, this has started to be formalised into Harvest Strategy Policies (HSP), where the actions needed for achieving agreed objectives, the monitoring and assessment processes, and the rules that control fishing intensity are specified (Smith et al., 2009). At the core of HSP is the clear definition of biological reference points (BRP) because stock status is defined by comparing these benchmarks to stock-performance indicators (SPI, e.g. spawning biomass and fishing mortality). If the SPI exceeds the BRP, management actions are triggered to control different aspects of the fishery or stock (Anonymous, 1995).

BRP are commonly expressed in terms of biomass (B_{BRP}) or fishing mortality (F_{BRP}) and consist of targets (representing the optimum state to deliver economic and/or social objectives) and limits (representing an unacceptable boundary which, if breached, triggers immediate significant management actions) (Anonymous, 1995). Threshold BRPs (an intermediate level between target and limit BRP) have also been adopted as 'early warnings' so an appropriate management response is generated before limit levels are breached (e.g. Hart et al., 2009).

Typically, optimal depletion (i.e. maximum sustainable yield, MSY), estimated from quantitative assessments, is used to define BRP. Due to data requirements, MSY estimation is only possible for data-rich fisheries. As an alternative, MSY proxies, which are commonly derived from per-recruit type analyses, can be used (Restrepo and Powers, 1999). These per-recruit proxies may be based on yield per-recruit (YPR) such as F_{max}, the fishing mortality that maximizes YPR, or $F_{0.1}$, the fishing mortality where the slope of the YPR curve is only one-tenth the slope at the origin. Alternatively, proxies can be based on a ratio of spawners per recruit with fishing mortality relative to spawners per-recruit without fishing mortality, referred to as spawning potential ratio (SPR). Based on work by Clark (1991, 1993), SPR ratios of 30%–40% are often proposed as defaults.

MSY proxies have been used for defining BRP for sharks as most species are data-limited (e.g. Chang and Liu, 2009; Tsai et al., 2011). Early BRP for sharks were general values across all species expressed as some proportion of the unfished biomass (B_U) (Bensley et al., 2010). To avoid arbitrary levels that may be too

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conservative/aggressive (Deroba and Bence, 2008), species-specific BRP that consider life history and population dynamics are recommended (Bensley et al., 2010; Brooks et al., 2010). Also, changes in natural mortality and to a lesser extent growth rate (e.g. through predator-prey dynamics) can affect BRP estimates (Collie and Gislason, 2001). Hence, in addition to considering differences in life-history traits, characterising uncertainty in these traits is essential when defining BRP for sharks (Brooks et al., 2010). Also, it is important that appropriate comparisons are then made between BRP and SPI.

The Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF)—the main shark fisheries of Western Australia (WA)—were used as a case study to develop BRP that incorporate life history uncertainty and to illustrate a new way for comparing BRP and SPI. These fisheries are managed via a range of input controls and gear restrictions, and of the 31 shark species taken, gummy (*Mustelus antarcticus*), dusky (*Carcharhinus obscurus*), whiskery (*Furgaleus macki*), and sandbar (*Carcharhinus plumbeus*) sharks comprise the bulk of the catch (McAuley and Simpfendorfer, 2003). These species account for approximately 80% of the fisheries' shark catch and represent the range of life history strategies of the other shark species caught. Hence, they are routinely monitored, assessed, and used as indicators for the status of all captured shark species (Braccini et al., 2013).

For gummy and whiskery sharks, female biomass (B) and F (derived from sex- and age-structured population dynamics models, PDM) are the SPI used for assessing stock status (e.g. Simpfendorfer et al., 2000b). For dusky and sandbar sharks, due to their considerable longevity and insufficient catch and effort time series, stock assessments are based on empirically-derived F estimates and stochastic demographic modelling (McAuley et al., 2007a). A general BRP ($B_{BRP} = 40\%\ B_U$) is currently used as the fishery target for all four species, and there are no specifications of F_{BRP} or B limits (B_{Lim}) and thresholds (B_{Thr}). In addition, the differences in life history traits with their corresponding uncertainties are not taken into account.

To improve management for the TDGDLF fishery, and to adopt a formal HSP, life history and fishery information was used to define species-specific limit, threshold and target BRP for the target shark species, making explicit consideration of uncertainty in life-history parameters. An approach for comparing distributions of BRP and SPI is also introduced.

2. Life history-based reference points

Several MSY proxies have been used to define BRP (YPR, SPR, or specifying a fishing mortality rate, F, that is some fraction of natural mortality, M), but the percentage of Spawning Potential Ratio (SPR) shows low sensitivity to parameter misspecification (Williams and Shertzer, 2003) and it has been recommended over other proxies (e.g. Mace, 1994; Williams and Shertzer, 2003; Chang and Liu, 2009; Tsai et al., 2011). Therefore, quantitative life history methods based on SPR and a Beverton–Holt stock-recruitment function (SRF) were used to define B_{BRP} and F_{BRP}. SPR is the ratio of the number of eggs produced over a recruit's lifetime under fishing and the number of eggs produced without fishing. Hence, SPR measures the proportional reduction in potential productivity due to fishing (Goodyear, 1993; Brooks et al., 2010). Specifying an appropriate %SPR is essential for defining BRP. Previous studies suggested different %SPR levels, ranging from 20 to 70% depending on species productivity (e.g. Mace, 1994; Clark, 2002). These studies, however, sought to identify a single value that would be appropriate for a range of different life histories for situations where the true SRF was unknown. Exploring the relationship between SPR and the slope at the origin of the SRF while simultaneously accounting for variability in life history parameters has not been investigated. Hence, we incorporated life history uncertainty and used the analytical method derived by Brooks et al. (2010) to calculate species-specific levels of %SPR. This method is suitable for sharks due to their large size at birth and small number of offspring which make recruitment much less variable than in teleosts or invertebrates and often allows for direct estimates of first year survival.

2.1. Calculation of species-specific reference points

Optimal depletion in number of fish is achieved at the SPR of maximum excess recruitment (SPR_{MER}) and is an appropriate metric for fisheries where catch data are in units of numbers of fish (Goodyear, 1996; Brooks et al., 2010). This is the case for the TDGDLF, where fishers report the number of sharks caught in catch and effort return logbooks. However, no single SPR_{MER} is optimal for all shark species (Brooks et al., 2010). Hence, we used life history information obtained from the literature (Simpfendorfer and Unsworth, 1998a, 1998b; Simpfendorfer et al., 2000a, 2002; McAuley et al., 2005, 2007a, 2007b, 2007c; Walker, 2010) (Table 1) to calculate species-specific levels.

Maturity-at-age was modelled using a logistic function and embryo sex ratio was set at 0.5. For gummy sharks, an exponential curve was used to model the relation between female size and number of pups (Walker, 2010). For whiskery, dusky and sandbar sharks, however, a fixed number of pups per female was assumed for all mature ages given the very weak relation between female size and number of pups. Growth was modelled using a modified form of the von Bertalanffy growth equation that fits the curve to a known size at birth (McAuley et al., 2005). Currently, there are no

Table 1
List of life history (with the assumed prior distribution when applicable) and selectivity parameters used. For the growth parameters, only the mean values used in the multivariate normal distribution are presented.

Parameter	Gummy shark	Whiskery shark	Sandbar shark	Dusky shark
Life history				
Maximum age (year)	*triangular*(16, 16, 20)	*triangular*(15, 15, 19)	*triangular*(30, 30, 39)	*triangular*(40, 40, 55)
Litter size (number)	*Exponential relation*	*triangular*(4, 16, 28)	*triangular*(4, 7, 10)	*triangular*(2, 10, 18)
Reproductive period (year)	1	2	2	*uniform*(2, 3)
Pup sex ratio	0.5	0.5	0.5	0.5
Age at 50% maturity (year)	*uniform*(4, 6)	*uniform*(6, 7)	*uniform*(13, 19)	*uniform*(26, 35)
Size at birth (cm)	33.5	25	42.5	75.3
Growth coefficient (k, year^{-1})	0.123	0.369	0.040	0.037
Asymptotic fork length (L_{inf}, cm)	201.9	120.7	244.2	374.4
Age at zero length (to, year)	−1.55	−0.6	−4.8	−3.3
Selectivity				
Alpha	40.81	64.01	7.52	25.43
Beta	26.63	18.53	117.18	33.26