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An overview of approaches used to assess the status of shark populations: experiences from the USA and ICCAT in the Atlantic Ocean

by

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Abstract

Assessment of Atlantic and other shark stocks has traditionally been impaired by scarcity of data that results in pervasive uncertainty. In light of the differing degrees of data availability that analysts are faced with, an approach where model choice is dictated by data type and quantity is advocated. This approach can be thought of as a stepwise procedure, with models increasing in complexity as a function of data availability. The most important characteristics of the biology and population dynamics of sharks, and the types of fishery data required by different modeling approaches as well as those that are generally available are first reviewed. A suite of methods that can be used for preliminary or more advanced assessment of shark stock status and to help guide management actions is then presented, drawing examples from experiences in the USA and the International Commission for the Conservation of Atlantic Tunas (ICCAT) assessment arenas.

1. Introduction

Assessments of shark population status are often limited by lack of data or relatively data-poor situations. It is thus important to have a variety of methodological approaches with data needs that are commensurate with those available. With that in mind, I briefly review a suite of methods that can be used for preliminary or more advanced assessment of shark stocks or to help guide management actions to conserve those stocks, drawing examples from experiences in the USA and the International Commission for the Conservation of Atlantic Tunas (ICCAT) assessment arenas. To set the background, I briefly review the most salient features of shark life history and population dynamics, noting the types of data that are often available as well as those generally missing. I continue with a similar overview of fishery data generally available.

1.1 Shark life history and population dynamics

It can be argued that some of the main vital rates of sharks needed to understand the dynamics of their populations are relatively well known for a variety of species, but other vital rates as well as processes, such as migration rates, stock-recruitment dynamics, spatial distribution of populations, and stock identity are generally very poorly known. Birth rates, which encompass a series of reproductive characteristics such as fecundity, reproductive periodicity, and proportion of mature and pregnant females, are generally best known because they can be observed empirically. Growth rates are estimated based on ageing of hard parts, typically vertebral centra, and while determination of maximum ages is particularly uncertain owing to sampling or methodological limitations, growth rates are relatively well known. In contrast, death rates, from natural mortality notably, are essentially unknown and are estimated using life history invariant methods based on life history and ecological theory.

One advantage of shark stock-recruit dynamics compared to that of teleosts is that sharks produce a small number of offspring owing to their life history strategy, which generally translates into a more direct relationship between stock and recruitment, also more independent of environmental influences. An interesting feature of the stock-recruit relationship in sharks is that the slope at the origin represents first-year survivorship (Brooks et al. 2010), which can be used to analytically obtain an estimate of the maximum lifetime reproductive rate, and hence steepness (see section 2.5). Although movements and migratory patterns of sharks are starting to be better understood, especially with the advent of archival tags, knowledge of migration rates is mostly inexistent. Also, identification of discrete stocks still remains a major challenge, especially for highly migratory, large pelagic species.

1.2 Fishery data available to model exploited population dynamics

One of the main problems with assessing shark populations has been historically that catches, if available, were aggregated, i.e., not broken down by species. In the USA, for example, species-specific recreational catch estimates were available relatively early (1981), but disaggregated commercial landings did not become available until 1992 at the earliest, depending on the State of reporting. Ideally, one would want to have catches by gear, area, and size (or age) for the whole period of exploitation, but that situation is obviously extremely rare. In the case of the USA and ICCAT, catches are available by species and gear (but only go back so far in time), but sufficient, systematic sampling of lengths of animals caught in all gears is not available, except for information obtained from scientific observer programs. Systematic sampling of catches for ageing has only been started very recently in the USA and only for the main directed fishery targeting the two-most commercially important species.

It is also generally very difficult to obtain good series of effort from the different gears because many sharks are caught in fisheries targeting other species. Catch rate information is available to a different extent in the USA vs. ICCAT. In the USA, a considerable number of CPUE series, both fishery-dependent and fishery-independent, are available for assessment. These series have very widely different degrees of temporal and geographical coverage and thus differ in their quality and suitability for use for assessment purposes. They are all statistically standardized, typically through GLM techniques, to attempt to remove the effects of factors unrelated to abundance (especially the fishery-dependent series), but many still show inter-annual fluctuations that are hard to reconcile with shark life history strategy (see section 2.3). Ideally, one would want a long-duration series showing good contrast (i.e. with increasing and decreasing trends resulting from different levels of fishing) that reflects true relative abundance, but that is hardly ever the case. Catch rates are also used sometimes to raise catch from effort, but the quality of those estimates (typically done for bycatch/discards) relies on the level of stratification of the data. Scientific observer programs have thus become very important because they allow to (1) ground-truth catch and landing information obtained from logbooks and seafood dealers, (2) provide size information for fitting of selectivity curves, development of series of average size, or producing catch curves, (3) possibly identify other factors that affect CPUE (see section Y), (4) provide information on status (condition of the animal before boarding) and disposition (fate of the animal after boarding) of the catch, and (5) provide biological samples.

The overall picture that emerges, however, is that both biological uncertainty and uncertainty in the level of catches are pervasive when trying to assess shark stocks. For this reason, it is sensible to have a set of frameworks that are only as complex as needed to make full use of the data available and to advocate a stepwise approach to attempt to assess the status or vulnerability of shark populations.

1.3 Stepwise approach to assessing status or vulnerability of shark stocks

The different methods that can be used to assess shark populations would fall along a continuum of increasing data richness, from the most data-poor situations that would allow assessment with rapid assessment techniques (RATs) to the most data-rich scenarios that could make use of very detailed age-structured population dynamics models, such as stock synthesis (Methot 2000), or even ecosystem-population dynamics models, such as SEAPODYM (Lehodey et al. 2008; Figure 1). These models, with emphasis on those more germane to data-poor situations, are briefly described next. The reader is referred to Cortés et al. (in press) and references therein for a much more in-depth description of all these models.

2. Models for data-poor situations

2.1 Rapid Assessment Techniques (RATs)

Some of the simplest Rapid Assessment Techniques (Walker, 2005) would include examining temporal trends in average size or in the proportion of mature fish. The simplest of these methods were proposed by Froese (2004), who presented three indicators of overfishing based on the concepts of “let them spawn”, “let them grow”, and “let the megaspawners live”. The first indicator measures the percentage of mature animals in the catch, with the target being to let 100% of fish spawn at least once before capture. This seems like the most sensible approach for sharks based on results from elasticity analysis, which show that the juvenile stage exerts the greatest influence on population growth and other work by Au et al. (2008) using a modified demographic model linking stock-recruitment and abundance-per-recruit relationships that also supported protection of the first few reproductive ages (young adults). Other support for this strategy comes from the prediction in demographic models that the reproductive value distribution (the number of offspring that remain to be born to a female of a given age) peaks shortly after maturity and work by Gallucci et al. (2006) showing that protection of juveniles and preservation of reproductive potential (the sum of the reproductive values of all individuals in a population) was the preferred management strategy for exploited shark populations. Protection of the first few breeding ages can be achieved through imposition of minimum size limits, as is the case in some shark fisheries worldwide. The second indicator is measured as the percentage of fish caught at optimum length, defined as “the length where the number of fish in a given unfished year class multiplied by their mean individual weight is maximum and where thus the maximum yield and revenue can be obtained”, and the target would be to catch 100% of fish within a predetermined range around that length. Froese (2004) further added that optimum length is generally slightly larger than length at first maturity, thus this does not seem like a sensible strategy for sharks given that this optimum size could include young breeding females. However, a possible management strategy could be to allow retention of only male specimens at optimum length. The third indicator is measured as the percentage of old, large fish in the catch and the target is 0%. While there is support for this strategy for many teleost stocks based on the fact that larger individuals generally have exponentially greater fecundity and that the larvae they produce may have higher survival than those of younger individuals (Birkeland and Dayton 2005), it appears that the contribution of older females to population growth is not so important in sharks (Cortés 2000) and thus present evidence does not support strategies that protect the oldest females in a population only, such as maximum size limits.

Other simple length-based methods include that of Beverton-Holt (1956), which has few data requirements (von Bertalanffy growth parameters, length at full vulnerability, and mean length of fully vulnerable animals), and that of Gedamke and Hoenig (2006), which further relaxes the equilibrium assumption of the Beverton-Holt method and allows estimation of multiple values of Z in a time series of mean lengths. However, these methods should be used cautiously given the numerous assumptions and recruitment dynamics always be considered.

There are other methods that could be applied in data-poor situations, such as the depletion-corrected average catch proposed by MacCall (2009), wherein the catch over an extended period of time is divided into a sustainable and an unsustainable component termed "windfall", which is associated with a one-time reduction in stock biomass, and whose size is expressed as being equivalent to a number of years of sustainable yield in the form of a "windfall ratio". Data required for calculation of the depletion-corrected average catch include the sum of catches and respective number of years, the relative depletion in biomass during that period, M, and an assumed ratio of F_{MSY} to M, which in the case of sharks could be set to 0.5. This method allows one to set Total Allowable Catches (TACs) with few data. Another recently developed method for managing fisheries with relatively scarce data uses catch and CPUE information to provide harvest control rules that produce a recommended biological catch (Little et al. 2011).

2.2 Ecological Risk Assessment (ERA)

Ecological Risk Assessments (ERAs), also known as Productivity and Susceptibility Analyses (PSAs), can be considered a rapid assessment technique. They are in fact a family of models that can range from simple (level 1) qualitative analyses to more quantitative (level 3) approaches, depending on data availability (Walker 2005; Hobday et al. 2007). They were originally developed to assess the vulnerability of stocks of species caught as bycatch in the Australian prawn fishery (Stobutzki et al. 2001a, b; Milton 2001), and although they only appeared about a decade ago they have now been used rather extensively to assess vulnerability to fishing of elasmobranchs and other marine taxa. Most PSAs have been semi-quantitative (level 2) approaches where the vulnerability of a stock to fishing is expressed as a function of its productivity, or capacity to recover after it has been depleted, and its susceptibility, or propensity to capture and mortality from fishing (Stobutzki et al. 2001a). Each of these two components, productivity and susceptibility, are in turn defined by a number of attributes which are given a score on a predetermined scale. Scores are then typically averaged for each index and displayed graphically on an X-Y plot (PSA plot). Additionally, vulnerability can be computed as the Euclidean distance of the productivity and susceptibility scores on the PSA plot. Applications to elasmobranchs have ranged from semi-quantitative PSAs (Stobutzki et al. 2002; Griffiths et al. 2006; Rosenberg et al. 2007; Patrick et al. 2010) to different degrees of quantitative analyses where the productivity component was estimated directly as r (intrinsic rate of population increase) in stochastic demographic models (Braccini et al. 2006; Zhou and Griffiths 2008; Simpfendorfer et al. 2008; Cortés et al. 2010; Tovar-Avila et al. 2010). The main advantages of PSAs can be summarized as: (1) being a practical tool to evaluate the vulnerability of a stock to becoming overfished based on its biological characteristics and susceptibility to the fishery or fisheries exploiting it, (2) they can be used to help management bodies identify which stocks are more vulnerable to overfishing so that they can monitor and adjust their management measures to protect the viability of these stocks, and (3) they can also be used to prioritize research efforts for species that are very susceptible but for which biological information is too sparse.

A Vulnerability Evaluation Working Group was formed by the National Marine Fisheries Service (NMFS) in the USA in 2008 to develop methodology to determine vulnerability for many of the data-poor stocks managed by NMFS. The main objective was to develop a flexible methodology that could be applied broadly to many different fisheries and regions, and the PSA or ERA approach was chosen after review of several risk assessment methods. One interesting aspect of the method developed, which was applied to 162 stocks from six fisheries, including Atlantic sharks, was the consideration of a data quality index to provide an estimate of information uncertainty (Patrick et al. 2009, 2010). An ERA for 11 species of pelagic elasmobranchs was also developed by the ICCAT Shark Working Group in 2008. This application was more quantitative because productivity was directly expressed as r, and susceptibility was calculated as the product of conditional probabilities of various events (Cortés et al. 2010). A similar approach, incorporating the inflection point of population growth curves and IUCN Red list status as additional metrics, was developed in parallel to the ICCAT ERA (Simpfendorfer et al. 2008). Finally, another quantitative (level-3) PSA was specifically applied to 26 stocks of Atlantic sharks in the USA (Cortés et al. 2008).

2.3 Statistical Analysis of Relative Abundance Trends

Temporal changes in catch-per-unit of effort (CPUE) have been used as indicators of stock status without having to fit a population dynamics model when only catch-effort data are available and can thus be considered to be data-poor situations to some extent. The implicit, fundamental assumption in this type of analysis is that CPUE reflects true changes in the relative abundance of the stock. Time series trends of CPUE can come from scientific surveys (fishery-independent) or be fishery-dependent. There are thus, especially in the case of fishery-dependent indices, factors that can affect the observed indices and which are unrelated to true abundance. Standardization of CPUE time series through statistical techniques is thus undertaken in an attempt to remove the effect of those factors. The reader is referred to Maunder and Punt (2004) for a review of some of the statistical techniques used to standardize CPUE time series. Interestingly, several of the most highly publicized reports of drastic declines in elasmobranch abundance have used this type of approach (Casey and Myers 1998; Baum et al. 2003, 2005; Baum and Myers 2004) and a large number of studies have now examined changes in relative abundance of elasmobranchs based on this method. Standardized CPUE time series are also often used as one of the inputs to more formal stock assessments. It is important, however, to examine those derived trends because they often show inter-annual fluctuations that seem incompatible with the biology of the species under study (Cortés et al. 2007).

2.4 Demographic models

Demographic models, in the form of life tables or their analog, Leslie matrices, are based on density independence and exponential population growth, and have been used widely to gain an understanding of the productivity and risk of overexploitation of elasmobranchs populations, and to address conservation issues by producing population metrics that can be used to generate mostly qualitative management measures. These models can easily be extended to incorporate uncertainty or variability in vital rates through Monte Carlo simulation. One caveat when using these models is that because natural mortality is almost always unknown for sharks, methods based on life-history invariants are used to estimate M. The majority of these methods, however, are based on equilibrium considerations and thus tend to underestimate the value of r when used in demographic models. Since these models are typically age-structured, they have the same data needs as age-structured stock assessment models, and focus on the female portion of the population. More specifically, data needs include: maximum age, age-specific fecundity, sex ratio at birth, frequency of parturition, proportion of females mature and breeding at age, age-specific M, growth function parameters, and length-mass relationships.

2.5 Composite method

A composite method incorporating life-history information, stock-recruitment considerations, and an estimate of depletion was recently developed by Brooks et al. (2010). This method is appealing because it allows derivation of reference points analytically without the need for fitting a stock assessment model. Briefly, the method calculates the Spawning Potential Ratio (SPR) at the point of maximum excess recruitment (MER), which can be derived analytically from the maximum lifetime reproductive rate (Myers et al. 1999), which is the product of the number of spawners produced by a recruit over its lifetime in the absence of fishing (or the net reproductive rate in life tables or matrix population models) and the slope at the origin of the stock-recruitment curve (typically a Beverton-Holt curve), which in sharks is simply first-year survival. To determine whether a stock is overfished, one further needs to estimate current depletion, which can be obtained from a relative index of abundance by dividing current abundance by unexploited abundance, and compare it to MER depletion (which is expressed in maximum lifetime reproductive rate terms). The final step consists of comparing current depletion to MER depletion times a scalar, p, which in sharks can be set to a value=1-M (Restrepo et al. 1998). Brooks et al. (2010) compared results for overfished status from stock assessments with predictions from the analytical method and found total agreement for the nine stocks of sharks for which an assessment estimate was available. The reader is referred to publications by Goodyear (2002) and Brooks et al. (2006, 2010) for details and derivations of the method.

3. Stock assessment models

More traditional stock assessment models can be used as data availability increases. In situations where only catch and CPUE data are available and biological information is limited, different forms of surplus production models can be used. Some of these applications can be quite sophisticated, incorporating Bayesian inference for parameter estimation, and thus several sources of uncertainty, as well as the ability to make probabilistic projections of stock status under alternative harvesting scenarios. Common criticisms with this type of approach, however, are that they disregard the age structure of the stock and the assumption that the all-inclusive surplus production term, “r”, responds immediately to changes in stock biomass. These models thus trade biological realism for mathematical simplicity. A variant of the traditional Schaefer surplus production model that is particularly applicable to sharks is the Pella-Tomlinson model (1969), which allows for the inflection point of the traditional hyperbolic relationship between stock size and net change to be shifted to the right, a situation that has been described for terrestrial and marine taxa with delayed density dependence, such as sharks. The position of the inflection point of population growth curves for several species of pelagic sharks was estimated by Cortés (2008) and found to vary from about 0.5 to values close to carrying capacity, K. Delay-difference models are somewhat of a bridge between surplus production models and the more complex age-structured models, which consider, although not explicitly, the age structure of the population and the lag of time that exists between spawning and recruitment. Age-structured models are even more complex and sophisticated, are more realistic biologically, but also have many more assumptions and necessitate more parameters to be provided or estimated. The life tables and matrix population models discussed earlier are a subset in the family of age-structured models. True statistical catch-at-age assessment models have not been applied for Atlantic sharks because of the lack of catch-at-age data. Length information, although limited, is easier to obtain and available in many cases, and has been used to estimate selectivity curves externally to age-structured production models. Current assessments plans in the USA and ICCAT aim to use length-based, but sex- and age-structured, models to assess Atlantic shark stocks.

4. Conclusions

While very sophisticated and more biologically realistic models (e.g., age-structured models, ecosystem/population dynamics models) are increasingly being developed to describe the dynamics of exploited marine populations, these models require that more parameter values be provided or estimated. In general, the choice of models should be determined primarily by the type and quantity of data available and not by the desire to include all interesting and possibly important processes, but for which no empirical data are available. There may be greater predictive return from investing in increased data quality, and quantity, rather than model sophistication. However, many species of sharks will require management action because of high catch susceptibility and low productivity long before sufficient data become available for assessment. A toolbox with multiple, flexible models that can be applied to situations with very different levels of data availability would thus be very useful.

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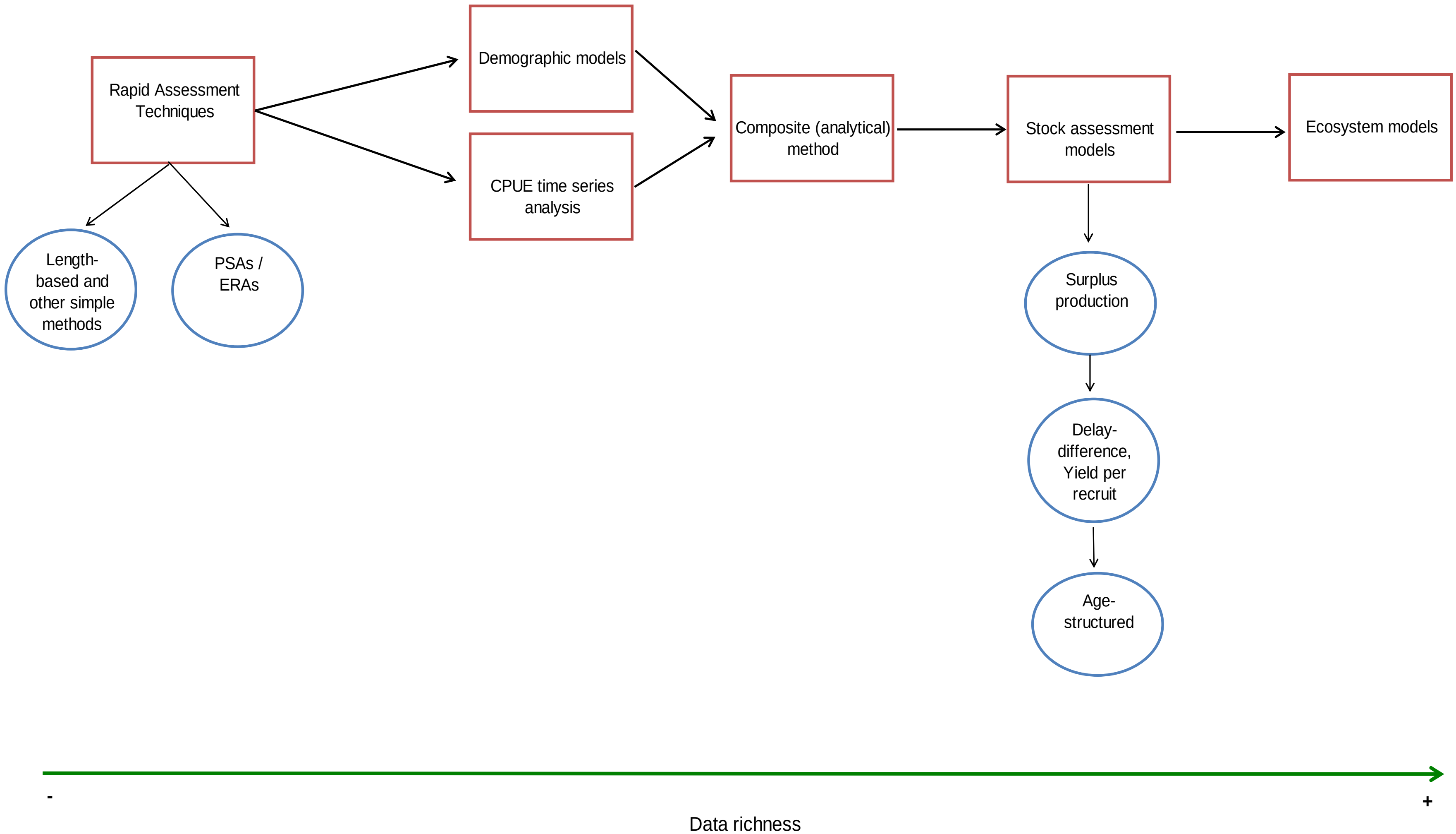

Figure 1. Schematic representation of a possible stepwise approach for assessing the status or vulnerability of exploited shark populations and providing management advice.