 Quantifying vulnerability of sharks and rays species in Indonesia: Is biological knowledge sufficient enough for the assessment?

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Abstract. Sharks and rays are vulnerable species, which are highly exploited in Indonesian waters but lacked of detailed information on their ecology and fisheries status. This research aims to assess the level of vulnerability of sharks and rays to overfishing using the maximum intrinsic rate of population increase ($r_{\text{max}}$), derived from the Euler-Lotka equation, as a proxy of extinction risk. It is calculated based on several biological parameters including fecundity, maximum age, age at maturity, and the number of offspring. Using $r_{\text{max}}$ calculation adapted to shark and ray life history traits by accounting for survival to maturity, we were able to calculate $r_{\text{max}}$ values for 26 out of 208 sharks and rays species present in Indonesia. This includes vulnerable species such as Mobula alfredi, Prionace glauca, and Pristis zijsron. This result showed that $r_{\text{max}}$ is a valuable tool which can be used to quantify extinction risk with some level of precision, but it also highlights the necessity to collect important biological information of the most vulnerable species to further estimate their status. This approach requires complementary information related to external threats such as habitat degradation, species economic value and threat level from local fishing effort and related fishing gears.

Keywords: euler-lotka equation, extinction risk, rays, $r_{\text{max}}$, sharks

1. Introduction

Ocean ecosystems are threatened by overfishing, climate change, habitat destruction, and pollution [1]. These threats lead to declining populations of marine wildlife and in some cases ecosystem collapses and species extinctions [2–4]. It is therefore important to monitor the status of marine species, in order to understand the nature and magnitude of these threats and develop better management approaches.

Sharks, rays and their relatives (class Chondrichthyes, herein ‘sharks’), are highly vulnerable to human pressures due to their conservative life history traits: slow growing, long-lived, late maturing and low fecundity [5]. These threats are particularly challenging to manage for sharks in Indonesia due to high species diversity, vast and complex spatial usage patterns, limited available scientific information on species status, and high fishing pressure.
Indonesia is home to a marine area located in the heart of the Coral Triangle, a mega-diverse region for marine biodiversity, which is home at least 207 Chondrichthyan species [6], includes sharks, skates, rays, and chimeras. Unfortunately, this high biodiversity is also experiencing high pressure due to extensive fishing activities conducted across many fishery hotspots. Indonesia has the highest shark landings of any country worldwide (> 100,000 tonnes/year) [7], with more than 200 targeted and by-catch fisheries capturing and retaining this species group [8], which forms an important source of income and livelihood for many coastal communities [9].

In addition to this high fishing pressure, detailed information on the life history, population status and species-specific fishing and trade of sharks are lacking. This raises concern on whether the population status of many shark species in Indonesia has already reached a tipping point towards a collapse. As such, an up-to-date national assessment of extinction risk is important for developing and prioritizing effective management efforts.

The aims of study to apply a simple proxy - maximum intrinsic rate of population increase ($r_{\text{max}}$) - for quantifying extinction risk of all known shark and ray species in Indonesia, based on life history characteristics[10, 11] as an alternative for other methods such as species-area relationship [12]. This approach was originally developed for teleost fish, which have different reproductive and life history strategies to most chondrichthyans. Therefore, we used a derivation of the Euler-Lotka equation that has been specifically adapted to shark and ray life history traits by accounting for survival to maturity [13]. We also assess the usefulness of this method for assessing shark species extinction risk and prioritizing shark conservation action, in Indonesia. This given limited data availability for many shark species, and the influence of other environmental and external human-induced pressures. Based on these findings, we offer recommendations for future shark conservation prioritization efforts in Indonesia, which may be useful for national red-listing processes, and the development of country-, species- and fishery-specific management strategies.

2. Materials and Methods

2.1. Species database preparation

During April-June 2017, desk-based data collection was conducted to compile information on all shark species present in Indonesia. Established species databases including the IUCN Red List website (www.iucnredlist.org/) and FishBase (fishbase.org/) were reviewed using a combination of keyword searches (e.g. “shark”, “ray”) with location set in Indonesia. We also reviewed available peer-reviewed and grey literature using similar keywords, to compile further information and crosscheck any missing species, duplicates, synonyms, and taxonomic updates.

Information collected, if available, included: species name (scientific name, English name and local name); taxonomy; habitat (depth, geographical distance, environment, emerging level); life-history traits (maximum body size, total body length/disk width, litter body size, size at maturity, fecundity, number of offspring, longevity, age at maturity, generation time and gestation time), which were separated by male or female characteristics, if applicable; species distribution (widespread, continuous or disjunctive, endemic status); geographic area found in Indonesia; population trend; exploitation level (target or by catch, catch quantity, fishery type: artisanal, commercial, recreational or localized, fishing target area: pelagic; demersal; deep water; reef; inshore; coastal, gear type); estimated economic value, based on how the species is used for commercial purposes; and IUCN Red List threat status. The information collected was reviewed by the shark and ray group at the Wildlife Conservation Society - Indonesia Program (WCS-IP), and further assessed by a team of national and international sharks and rays experts during an expert consultation workshop on sharks and rays held on 29-30th August 2017 in the office of Ministry of Maritime Affairs and Fisheries (MMAF), Jakarta.

2.2. Extinction risk analysis

The maximum intrinsic rate of population increase ($r_{\text{max}}$) is a common method used to assess extinction risk in teleost fishes, using a derivative of Euler-Lotka equation:
\[ \sum_{t=1}^{\omega} l_t b_t e^{-r t} = 1 \]  

(1)

Where \( t \) is age, \( \omega \) is maximum age, \( l_t \) is the proportion of individuals that survive to age \( t \), \( b_t \) is fecundity at age \( t \), and \( r \) is the rate of population increase. \( e \) is a mathematical constant equals to 2.718.

The equation was revised by including annual survival of adults \( p = e^{-M} \) where \( M \) represents species-specific instantaneous natural mortality rate [14]. This also allows the exclusion of survival to maturity \( (l_{\text{mat}}) \) and annual fecundity \( (b) \) from the sum and to have the equation rewritten as:

\[ l_{\text{mat}} b \sum_{t=0}^{\omega} p^{t-\text{mat}} e^{-r \text{ mat} t} = 1 \]  

(2)

This method has been previously applied to sharks in Indonesia [10], but it can be problematic, since survival to maturity \( (l_{\text{mat}}) \) is usually ignored or not fully accounted for, by equating it to 1 [15], assuming \( \alpha = b \).

The equation later adapted to account for low survival to maturity in sharks [13]:

\[ \alpha = e^{\text{mat}} - p(e^{M})^{\text{mat} t} \]  

(3)

While including:

\[ \alpha = l_{\text{mat}} b \]  

(4)

With calculation of the proportion of individuals surviving to maturity using:

\[ l_{\text{mat}} = (e^{-M})^{\text{mat} t} \]  

(5)

With the assumption that natural mortality is exponentially distributed, the average mortality rate is the mean of that distribution, equals to the reciprocal of average life-span such that \( M = \frac{1}{\omega} \) [16]. \( \omega \) is then revised to be an estimate of average life-span in years, and since this data is difficult to obtain, [13] assumed that \( \omega = (a_{\text{max}} + a_{\text{mat}})/2 \) (midpoint between age at maturity and maximum age).

We also calculated the annual production of female offspring as equation (6) with sex ratio = 0.5 [10].

\[
\text{Annual Production} = \frac{\text{mean number of offspring}}{\text{breeding interval (fecundity)}} \times \text{sex ratio}
\]

(6)

We applied this final version of \( r_{\text{max}} \) equation to our dataset. To do so, we first extracted the following variables from the species database: (1) maximum age (female), (2) mean age at maturity (female), (3) mean number of offspring (4) and fecundity and then applied them to the \( r_{\text{max}} \) equation. If maximum age (female) value was not available, we estimate this variable by calculating the sum of mean age at maturity (female) and (5) mean generation time. When there is only categorical data available for fecundity (low or high), we used the minimum and maximum continuous value. Therefore, low fecundity is every three years, while high fecundity is every year.

We also calculated the \( r_{\text{max}} \) value using the assumption that \( \alpha = b \) to compare our results with an equation which excludes the assumption of survival into maturity [15], and compared the \( r_{\text{max}} \) extinction risk results with current IUCN Red List threat categories. To categorize the resilience level of the \( r_{\text{max}} \) value, we used categorization using ratings described by FishBase [17] which is as following (table 1).
Table 1. Fishbase rating of resilience level of a species using $r_{\text{max}}$ values.

| High       | Medium    | Low       | Very low |
|------------|-----------|-----------|----------|
| >0.5       | 0.16-0.5  | 0.05-0.15 | <0.05    |

We also checked the linear correlation between the $r_{\text{max}}$ values with age at maturity and with a number of offspring for each species ($l_{\text{max}}$). If we found a significant correlation, we checked the residual distribution of the model and ran a quantile regression model instead if any pattern was detected (using the conditional median, package mblm [18]).

$r_{\text{max}}$ estimation was conducted using Wolfram Alpha: Computational Intelligence

\[ l_{\text{max}} = (e^{-M})^{\text{cmat}} \]  

(www.wolframalpha.com/) while all statistics were done using R statistical programming language (R Core Team 2018).

3. Results and Discussion

From 268 possible species present in Indonesia, based on our initial desktop search, 208 species were confirmed to be found in Indonesia waters. Most of the available information for each species was deemed to be incomplete to calculate the $r_{\text{max}}$, which resulted in only 26 species (13\%) which could be assessed using the $r_{\text{max}}$ approach [13] (table 2). We found that the distribution of the $r_{\text{max}}$ values for available species is slightly right-skewed (figure 1) (table 2).

The $r_{\text{max}}$ calculations are corresponding relatively well to current IUCN Red List threat categories of the assessed species (IUCN red list website; accessed 10th January 2019), with most threatened (i.e. VU, EN, CR) species falling in very low, low or moderate resilience. Some of the least concerned or near threatened species fall into the high resilience category.

Comparing $r_{\text{max}}$ values calculated using the previous approach [13] with $r_{\text{max}}$ values which exclude the survival to maturity factor shows that the other approach [15] consistently overestimates $r_{\text{max}}$ and therefore underestimates extinction risk. The difference percentage value is on average 22.36±2.12, higher using the second one than the first one.

We did not find a significant correlation between $r_{\text{max}}$ and age of maturity (figure 3.a). But we did find a significant correlation between a number of offspring per year and $r_{\text{max}}$ values (p-values <0.001, %R²=15\%), which means that species with a higher number of offspring per year has better resilience (higher $r_{\text{max}}$ value) (figure 3.b).

The $r_{\text{max}}$ method used in this study has been shown to be a simple and effective method for estimating shark species extinction risk in Indonesia, based on life-history parameters. The extinction risks calculated also correspond relatively well with the IUCN Red List threat statuses, with threatened species (i.e. VU and EN) mainly falling in very low, low or moderate resilience and Least Concerned (LC) or Near Threatened (NT) species fall into the moderate to high resilience. Unfortunately, we did find several discrepancies. The most notable outliers are: Hardnose Shark (*Carcharhinus macloti*), Bentfin Devil Ray (*Mobula thurstoni*), Bull Shark (*Carcharhinus leucas*), Bluntnose Sixgill Shark (*Hexanchus griseus*), Sandbar Shark (*Carcharhinus plumbeus*), Great Hammerhead (*Sphyrna mokarran*), Green Sawfish (*Pristis zijsron*), Winghead Shark (*Eusphyra blochii*), Scalloped Hammerhead (*Sphyrna lewini*), Snaggletooth Shark (*Hemipristis elongata*) and Blue Shark (*Prionace glauca*). For example, Great Hammerhead is under Endangered status in IUCN while having high
resilience (high $r_{\text{max}}$). The Endangered status might be related to the species for having their nursery area within the coastal area [18, 19], thus increasingly threatened by fishing pressure and habitat degradation. This is probably the case for Green Sawfish, Winghead Shark (also used as crab bait; anecdotal information), and Scalloped Hammerhead as well. Blue Shark is also often being caught as tuna bycatch [20, 21]. In general, this discrepancy might be related to the shortfall of $r_{\text{max}}$ to account for the magnitude of anthropogenic threats and species-specific vulnerability to these threats (i.e. habitat degradation and fishing pressure).

Table 2. List of species rank based on their corresponding $r_{\text{max}}$ values and their associated risk and IUCN categories. IUCN Red List Categories: EX - Extinct, EW - Extinct in the Wild, CR - Critically Endangered, EN - Endangered, VU - Vulnerable, NT - Near Threatened, LC - Least Concern, DD - Data Deficient.

| Common name            | Scientific name              | $r_{\text{max}}$ [13] | Resilience (FishBase rating) | IUCN    |
|------------------------|------------------------------|------------------------|------------------------------|---------|
| Reef Manta Ray         | Mobula alfredi               | 0.042                  | very low                     | VU      |
| Giant Manta Ray        | Mobula birostris             | 0.042                  | very low                     | VU      |
| Spotted Eagle Ray      | Aetobatus ocellatus          | 0.065                  | low                          | VU      |
| Hardnose Shark*        | Carcharhinus macloti         | 0.070                  | low                          | NT      |
| Pelagic Thresher       | Alopias pelagicus            | 0.074                  | low                          | VU      |
| Bigeye Thresher*       | Alopias superciliosus        | 0.078                  | low                          | VU      |
| Bentfin Devil Ray*     | Mobula thurstoni             | 0.089                  | low                          | NT      |
| Bull Shark*            | Carcharhinus leucas          | 0.091                  | low                          | NT      |
| Dusky Shark            | Carcharhinus obscurus        | 0.096                  | low                          | VU      |
| Giant Devil Ray        | Mobula mobular               | 0.110                  | low                          | EN      |
| Shortfin Mako          | Isurus oxyrinchus            | 0.116                  | low                          | VU      |
| Smalltooth Sand Tiger  | Odontaspis ferox             | 0.134                  | low                          | VU      |
| Bluntnose Sixgill Shark* | Hexanchus griseus         | 0.147                  | low                          | NT      |
| Silvertip Shark        | Carcharhinus albimarginatus  | 0.149                  | low                          | VU      |
| Australian Sharpnose Shark | Rhizoprionodon taylor     | 0.152                  | medium                      | LC      |
| Silky Shark            | Carcharhinus falciformis     | 0.157                  | medium                      | VU      |
| Sandbar Shark*         | Carcharhinus plumbeus        | 0.163                  | high                        | VU      |
| Great Hammerhead*      | Sphyrna mokarran             | 0.194                  | high                        | EN      |
| Green Sawfish*         | Pristis zijsron              | 0.213                  | high                        | CR      |
| Winghead Shark*        | Eusphyra blochii             | 0.243                  | high                        | EN      |
| Tiger Shark            | Galeocerdo cuvier            | 0.245                  | high                        | NT      |
| Oceanic Whitetip Shark | Carcharhinus longimanus      | 0.268                  | high                        | NT      |
| Zebra Shark            | Stegostoma fasciatum         | 0.303                  | high                        | NT      |
| Scalloped Hammerhead*  | Sphyrna lewini               | 0.305                  | high                        | EN      |
| Snaggletooth Shark*    | Hemipristis elongata         | 0.342                  | high                        | VU      |
| Blue Shark*            | Prionace glauca              | 0.628                  | high                        | NT      |

* = $r_{\text{max}}$ values/species resilience does not properly corresponding to the IUCN category.
Figure 1. Histogram of $r_{\text{max}}$ values of sharks and rays used in this analysis. Dotted lines show the resilience categories based on Fishbase rating (table 1). Normality curve is also added to the histogram.

Figure 2. Values of $r_{\text{max}}$ using equation, compared to $r_{\text{max}}$ calculation, with the first approach including survival to maturity into consideration ($r_{\text{max}}$ [13]; $r_{\text{max}}$ [15]).
Figure 3. (a) Non-significant correlation between $r_{\text{max}}$ values with age at maturity was found. The values at each point represent a number of offspring per year for each species. (b) Significant relationship (p-value = <0.001) was found between $r_{\text{max}}$ values with number of offspring per year.

Furthermore, $r_{\text{max}}$ calculation is based on life-history traits only, and therefore only provides intrinsic extinction risk of species. This fails to take into account the magnitude of threats, the vulnerability of species to these threats and observed population and distribution declines, which are taken into account during IUCN Red Listing. This may explain the discrepancy categorization on some of the species, whose unique morphologies and habitat make them highly vulnerable to be captured in both targeted and by-catch fisheries. This extra risk factor would not be included within the $r_{\text{max}}$ calculation. An environmental condition also needs to be considered as depth that scaled of the relationship with temperature also influenced productivity of chondrichthyan [22].
Our results showed that $r_{\text{max}}$ values calculated with inclusion of survival to maturity result in lower $r_{\text{max}}$ values, which makes the approach more conservative [13]. The importance of the number of offspring which species produced yearly in order to maintain higher resilience against various extinction risks [13]. The importance of aging study and bias consideration since the age underestimation may lead to an underestimation of longevity and produced biased growth and mortality parameters [22].

In general, these results highlight the problem of limited data availability for conducting science-based assessments of species extinction risk and conservation prioritization for sharks in Indonesia. As we were only able to analyze 13% of all shark species in Indonesia, $r_{\text{max}}$ might not be an effective method for assessing the extinction risk of this highly valuable group, especially when conservation concern is high and management action is urgently needed. Other more robust and readily available methods need to be explored so that local extinction risk can be estimated under minimum data availability, and appropriate management actions can be designed.

Another point of concern is the exclusion of fishing pressure data in preparation of the risk categorization. As Indonesia’s shark population status is highly influenced by fishing pressure, from both targeted or by catch fisheries, it is important to use an evaluation method which can incorporate life history of the species and species-specific external threats/fishing pressure. What is more, this data may need to be site and fishery specific, in order to develop appropriate management actions. Finally, conservation prioritization should not only consider biological and threat values of species but also conservation opportunity and the likelihood of success, in order to understand the resources and efforts required to save species.

Overall, although the use of $r_{\text{max}}$ can help us to assess the extinction risk of shark species in Indonesia based on their life history characteristics, using this as part of national conservation prioritization efforts still requires complementary data to understand local threats and conservation opportunity. Since life history data is lacking for many shark species, exploration of other robust and easily-used approaches to prioritize conservation action are needed to support scientifically-sound management decisions, especially for an area such as Indonesia, with high marine biodiversity and high dependency on marine resources.

4. Conclusion

In conclusion, $r_{\text{max}}$ is a valuable tool which can be used to quantify extinction risk with some level of precision, but it also highlights the necessity to collect important biological information of the most vulnerable species to further estimate their status. This approach requires complementary information related to external threats such as habitat degradation, species economic value and threat level from local fishing effort and related fishing gears.

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