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Estimating fleet-specific allocations of spawning potential ratios[1]

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ABSTRACT

In 2024, the ALBWG advised the WCPFC NC and IATTC on how to interpret fishing intensity in spawning potential ratio (SPR) units, based on an analysis of the relationships between fleet-specific SPRs and measures of catch and effort for North Pacific Albacore Tuna (NPALB). However, the ALBWG did not tackle the question: if an allocation of fleet-specific SPRs are set based on the current total SPR but subsequently, changes to the total SPR are needed, how is the new total SPR to be allocated such that relative benefits to each fleet would be maintained at the same or some other desired level? In this study, we show how: 1) SPRs are related to the Poisson-binomial distribution; 2) to use the Poisson-binomial distribution to calculate the fleet-specific share of benefits from the fleet-specific SPRs; 3) to use Excel (or some other platform) to estimate the fleet-specific SPRs such that they result in the specified total SPR and at the same time, result in the specified fleet-specific share of benefits; and 4) as an example, to convert the fleet-specific SPRs into catch and/or effort controls based on the relationships previously established by the ALBWG. The Excel code and R scripts associated with this study were demonstrated and made available to the ALBWG. The tests of the Excel code showed that Solver was able to solve the equations for nine aggregated fleets and a series of desired total SPR values ranging from $F20_{\%SPR}$ to $F90_{\%SPR}$, such that the desired total SPR values were met, while the share of benefits for each fleet were maintained at fixed levels. This study demonstrates one potential way to estimate the fleet-specific SPRs such that the desired total SPR values were met, while the share of benefits for each fleet were maintained at the desired levels. These fleet-specific SPRs could in turn be related to catch and/or effort controls. We recommend that the ALBWG consider this information when providing advice on relating reductions in fishing intensity to more traditional measures of catch and/or effort.

INTRODUCTION

The Albacore Working Group (ALBWG) of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC) conducts the stock assessments for North Pacific albacore tuna (NPALB) (e.g., ALBWG 2023). The NPALB stock is managed by two regional fisheries management organizations (RFMOs): the Western and Central Pacific Fisheries Commission's Northern Committee (WCPFC NC) and the Inter-American Tropical Tuna Commission (IATTC) in the Western and Central Pacific Ocean (WCPO) and the Eastern Pacific Ocean (EPO) respectively. At the request of the RFMOs, the ALBWG conducted a management strategy evaluation (MSE) for NPALB during 2015 – 2021 (ALBWG 2021). The RFMOs subsequently used the MSE results to develop harvest strategies for the stock, which were adopted in 2023 (WCPFC NC Harvest Strategy 2023-01; IATTC Resolution C-23-02).

These harvest strategies include harvest control rules (HCRs) that mandated reductions in fishing intensity ($F_{\%SPR}$) in terms of spawning potential ratio (SPR), if the female spawning stock biomass (SSB) fell below threshold and limit reference points. The threshold and limit reference points are $30\%SSB_{current,\ F=0}$ and $14\%SSB_{current,\ F=0}$, respectively, which are 30% and 14% of the current, dynamic SSB under zero fishing, and hence fluctuates with changes in recruitment. The harvest strategies also aim to maintain fishing intensity around the target reference point of $F45_{\%SPR}$, which is the fishing intensity that results in the stock producing a SPR of approximately 45%. However, given that WCPFC NC and IATTC have traditionally used catch and effort controls to manage fisheries, both RFMOs requested that further work be performed to relate reductions in fishing intensity to more traditional measures of catch and/or effort.

The ALBWG responded to the RFMOs' requests by providing advice on how to interpret fishing intensity in SPR units into management measures (ALBWG 2024). This advice was based on an analysis of the relationships between fleet-specific SPRs and measures of catch and effort for North Pacific Albacore Tuna (NPALB) (Teo et al. 2024). Teo et al. (2024) separated the annual total SPR estimated in the stock assessment into fleet-specific SPRs, and showed that the fleet-specific SPRs had very strong relationships with the catch for all fleets, and moderately strong relationships with the effort for several fleets that target NPALB. Therefore, the RFMOs will likely be able to manage the total and fleet-specific SPRs by managing the catch and/or effort of the fleets.

However, Teo et al. (2024) did not tackle the question: if the RFMOs sets an allocation of fleet-specific SPR based on the current total SPR but subsequently needs to change the total SPR, how do the RFMOs reallocate the new total SPR such that relative benefits to each fleet would be maintained at the same or some other desired level? For example, if estimated SSB falls below the $30\%SSB_{current,\ F=0}$ threshold reference point, the RFMOs are expected to follow the harvest strategy and reduce the overall fishing intensity. The RFMOs may also decide to allocate fishing intensity or reductions in fishing intensity for individual fleets and/or RFMO Members. The RFMOs have allocated the proportions of catch and/or effort for each fleet and/or RFMO Members using historical periods or specific values. However, it is currently not clear how to do so in terms of SPRs. In this study, we show that SPRs are closely related to the Poisson-binomial distribution and therefore, the same proportional change in the total SPR and the fleet-specific SPRs do not necessarily result in the same proportional change in the benefits for the fleets. Therefore, there is a need for the RFMOs to be able to manage the total SPR of a stock by changing the fleet-specific SPRs to result in the desired total SPR but also be able to manage the relative share of benefits for each fleet at the same time.

In this study, we show how: 1) SPRs are related to the Poisson-binomial distribution; 2) to use the Poisson-binomial distribution to calculate the fleet-specific share of benefits from the fleet-specific SPRs; 3) to use Excel (or some other platform) to estimate the fleet-specific SPRs such that they result in the specified total SPR and at the same time, result in the specified fleet-specific share of benefits; and 4) as an example, convert the fleet-specific SPRs into catch and/or effort controls based on the relationships in Teo et al. (2024). In addition, we will also discuss an alternative approach used by the US Pacific Fisheries Management Council (PFMC) to use SPR to manage US West Coast groundfish fisheries.

METHODS

Spawning potential ratio and the Poisson-binomial distribution

The total fishing intensity on a stock can be expressed in terms of total SPR (p_{tot}), and is related to the fleet-specific SPR by,

$$P_{tot} = \prod_{n} p_i \tag{1}$$

where p_i is the fleet-specific SPR of the ith of n fleets. It is important to note that in terms of SPR units, the population can either contribute to spawning potential or benefit the fishery (i.e., catch or removals). Natural mortality of the population is not considered because SPR is calculated relative to an unfished population. Therefore, the total benefits accrued by the fleets are $1 - p_{tot}$, and that,

$$1 - P_{tot} = 1 - \prod_{n} p_i \neq \prod_{n} (1 - p_i) \tag{2}$$

Therefore, if we want to manage the fishing intensity on the stock by changing the total fishing intensity by proportion x to a new level (i.e., $P_{tot,new} = xP_{tot}$) but want to maintain the relative share of benefits for each fleet, we cannot simply use $x^{1/n}p_i$ to calculate $p_{i,new}$.

Instead, we can conceptualize p_i as the probability of successfully flipping heads for the ith out of n non-identical, biased coins, which is equivalent to the Poisson-binomial distribution (Hong 2013; Tang and Tang 2023). The Poisson-binomial distribution describes the distribution of the sum of independent and non-identically distributed Bernoulli trials, where the probability of success of each trial varies (Hong 2013). A special case of the Poisson-binomial distribution would be the binomial distribution, in which the probabilities of success for all trials are identical. Interestingly, the Poisson-binomial distribution remains an active field of research because it has applications in modern technology (e.g., machine learning, causal inference), and is linked to other fields of mathematics (e.g., algebraic geometry, mathematical physics) (Tang and Tang 2023). The Poison-binomial distribution can be denoted as $X = PB(p_1, \dots, p_n)$, where *X* is a discrete, random variable and the probability of *X* having *k* successes is

$$\mathbb{P}(X = k) = \sum_{A \subset [n], |A| = k} \prod_{j \in A} p_j \prod_{j \notin A} 1 - p_j \tag{3}$$

where the sum ranges over A, which is a subset of $[n] = \{1, \dots, n\}$ and has *k* elements. The summation of set A accounts for all possible combinations when you choose *k* elements from the full set [*n*]. The number of combinations in set *A* would be $C(n, k) = \frac{n!}{k!(n-k)!}$. For example, if *n* = 3, and *k* = 2, the set *A* would be $\{\{1,2\},\{1,3\},\{2,3\}\}$.

Therefore, the total SPR (P_{tot}) is equivalent to $\mathbb{P}(X = n)$, which is the probability of all *n* trials being successful. It is important to note that, when we use the Poisson-binomial distribution to calculate fleet-specific benefits, Eqn 3 calculates the sum of the spawning successes from all *n* fleets. However, we are more interested in calculating the expected removals in SPR units for specific fleet *i*. Therefore, we modified Eqn 3 into

$$\mathbb{P}(X = m|i) = \frac{1}{m} \sum_{A \subset [n], |A| = m, A = \{i, \dots\}} \prod_{j \notin A} p_j \prod_{j \in A} 1 - p_j \tag{4}$$

where $\mathbb{P}(X = m|i)$ is the probability of *m* failures that includes the *i*th trial out of *n* trials, and can be thought of as the expected removals or benefits in SPR units for the *i*th fleet that is shared among *m* fleets out of a total of *n* fleets, and the set *A* only includes combinations inclusive of fleet *i*. Therefore, the total benefits for fleet *i* is the cumulative distribution function

$$\mathbb{P}(X \geq 1|i) = \sum_{m=1}^{n} \frac{1}{m} \sum_{A \subset [n], |A| = m, A = \{i, \dots\}} \prod_{j \notin A} p_j \prod_{j \in A} 1 - p_j \tag{5}$$

And the total benefits for all fleets is

$$\mathbb{P}(X \geq 1) = \sum_{m=1}^{n} \sum_{A \subset [n], |A| = m} \prod_{j \notin A} p_j \prod_{j \in A} 1 - p_j \tag{6}$$

And the relative share of benefits for fleet *i* is

$$\frac{\mathbb{P}(X \geq 1|i)}{\mathbb{P}(X \geq 1)} \tag{7}$$

Estimation

However, we note that total SPR is

$$P_{tot} = \prod_{n} p_i = \mathbb{P}(X = 0) = 1 - \mathbb{P}(X \geq 1) \tag{8}$$

and we want to manage the fishing intensity on the stock by changing the total SPR (i.e., setting $p_{tot,new}$) but want to maintain the relative share of benefits for each fleet (Eqn 7). As far as we currently know, there are no analytical solutions to do so. Therefore, we took a simple numerical approach to solve for $p_{i,new}$ by minimizing the following sum of squares

$$\left(P_{tot,new} - \prod_{n} p_{i,new}\right)^2 \tag{9}$$

And

$$\sum_{i} \left(\frac{\sum_{m=1}^{n} \frac{1}{m} \sum_{A \subset [n], |A|=m, A=\{i,\dots\}} \prod_{j \notin A} p_{j,new} \prod_{j \in A} 1 - p_{j,new}}{\sum_{m=1}^{n} \sum_{A \subset [n], |A|=m} \prod_{j \notin A} p_{j,new} \prod_{j \in A} 1 - p_j, new} - \frac{\mathbb{P}(X \geq 1|i)}{\mathbb{P}(X \geq 1)} \right)^2 \tag{10}$$

For this study, the above equations were coded in Microsoft Excel, and Eqns 9 and 10 were minimized with Solver. The equations are conceptually simple but lengthy, and tedious to code in Excel. The Excel code was checked by comparing the calculations of Eqn 3 with the calculations from R scripts using the R library 'poibin' (Hong 2013).

Example for North Pacific Albacore Tuna

As an example, we used the abovementioned Excel code for the NPALB fleet groupings described in Teo et al. (2024), which had nine aggregated fleets: 1) Japan longline; 2) Japan pole-and-line; 3) US longline; 4) Taiwan longline; 5) Korea longline; 6) China longline; 7) Vanuatu and others longline; 8) EPO surface; and 9) Driftnet and miscellaneous. The desired share of benefits for each fleet were calculated from Eqn 7, with p_j assumed to be the geometric mean of the fleet-specific SPRs for 2002 – 2004 from the 2023 stock assessment (Teo et al. 2024). The geometric mean of the total SPR for 2002-2004 was estimated to be $F38.9_{\%SPR}$. A series of desired total SPR values ranging from $F20_{\%SPR}$ to $F90_{\%SPR}$ were used to test the ability of the Excel code to estimate the fleet-specific SPRs that would meet the conditions expressed in Eqns 9 and 10 (i.e., meet the desired total SPR values, while maintaining the share of benefits for each fleet). In addition, the estimated relationships between fleet-specific SPRs and catch and/or effort from Teo et al (2024), or other relationships, could be used to convert the estimated fleet-specific SPRs into potential catch and/or effort limits for the desired total SPRs.

RESULTS AND DISCUSSION

As far as we know, previous studies have not illustrated or used the close relationship between SPRs and the Poisson-binomial distribution. Using the Poisson-binomial distribution allows for the calculations of the fleet-specific share of benefits in SPR units despite the non-additive nature of SPR calculations. The Excel code and R scripts associated with this study will be demonstrated and made available to the ALBWG.

The tests of the Excel code showed that Solver was able to minimize Eqns 9 and 10 for a series of desired total SPR values ranging from $F20_{\%SPR}$ to $F90_{\%SPR}$, such that the desired total SPR values were met, while the share of benefits for each fleet were maintained at the mean of 2002-2004 levels. If so desired, we also show that the estimated relationships between fleet-specific SPRs and catch and/or effort from Teo et al (2024), or other relationships, could be coded in Excel and used to convert the estimated fleet-specific SPRs into potential catch and/or effort limits for the desired total SPRs.

It may also be useful for the ALBWG to understand alternative approaches to using SPRs in managing fisheries. For example, the US PFMC generally uses SPR-based MSY-proxies (e.g., $F45_{\%SPR}$) to manage US West Coast groundfish fisheries with data-rich assessments (Pacific Fishery Management Council 2024). For these fisheries, an overfishing limit (OFL) for catch is generally calculated by applying the MSY-proxy (e.g., $F45_{\%SPR}$) to the best estimate of current biomass. A scientific uncertainty buffer is then applied to the OFL to calculate the acceptable biological catch (ABC). In addition, precautionary adjustments, based on the harvest control rules, as well as other adjustments, like bycatch, social, economic, and ecological adjustments, are made to the ABC, to obtain the annual catch limit (ACL) for a stock or part thereof. Depending on stock, this ACL may then be apportioned and allocated to various sectors of the fisheries that catch this stock (e.g., Fig. 1).

However, it is unclear if the WCPFC NC and IATTC would be interested in using a similar approach as the US PFMC. In general, the US PFMC converts a SPR into an ACL, which is then allocated to various sectors of the fishery. In contrast, the WCPFC NC and IATTC have requested the ISC examine effort controls for some but not all fleets. Therefore, it is likely that the RFMOs would use a mixture of catch and effort controls for NPALB. In addition, the NPALB MSE showed that a mixture of catch and effort controls for NPALB would achieve the management objectives of the RFMOs (ALBWG 2021).

In the future, the RFMOs may decide to reduce the overall fishing intensity for NPALB and allocate fishing intensity or reductions in fishing intensity for individual fleets and/or RFMO Members. This study demonstrates one potential way to estimate the fleet-specific SPRs such that the desired total SPR values are met, while the share of benefits for each fleet were maintained at the desired levels. These fleet-specific SPRs could in turn be related to catch and/or effort controls. We recommend that the ALBWG consider this information when providing advice to the RFMOs on relating reductions in fishing intensity to more traditional measures of catch and/or effort.

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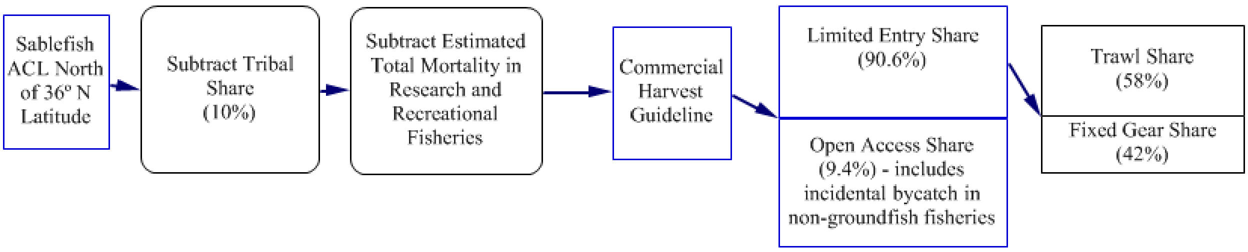

Figure 1. Fixed intersector allocations of sablefish north of 36°N (Pacific Fishery Management Council 2024).