

RESILIENCY FOR NORTH ATLANTIC SWORDFISH USING LIFE HISTORY PARAMETERS

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SUMMARY

North Atlantic swordfish have been fished at high F/s until recently. This reduction in fishing pressure rebuilt the populations, and is touted as a success story in ICCAT management. However, reasons for this are not well understood, and we take a mathematical approach to estimating steepness based on life history data and studies, and then use that information in assessing resiliency in time of rebuilding to target and limit reference points for this stock. Steepness is implicitly a very important parameter in this and its effect on resiliency is quantified. In addition, we quantify a construct to assess risk to the stock and the fishery. Reference points set undue burden on either the fisherman or the conservationists, and balancing these risks in a mathematical construct is presented here. While 0.4 B_{MSY} maybe a good target for a limit it creates a high type II error, i.e. failing to protect the stock when needed 80% of the time. If we try to reduce this risk, it increases the risk to a loss in yield when it is not required. We suggest a limit around 0.6 S_{MSY} for this stock so as to balance the risk between the resource and the fishery.

RÉSUMÉ

L'espada de l'Atlantique Nord a été pêché à des niveaux élevés de F jusqu'il y a peu. Cette réduction de la pression de la pêche a rétabli les populations et est présenté comme une réussite de la gestion de l'ICCAT. Néanmoins, les raisons expliquant ceci ne sont pas bien comprises et nous avons appliqué une approche mathématique pour estimer la pente à l'origine de la relation stock-recrutement (steepness) sur la base des données du cycle de vie, et avons ensuite utilisé cette information pour évaluer la résilience nécessaire en termes de temps pour que ce stock se rétablisse aux points de référence cible et limite. La pente steepness est implicitement un paramètre très important dans ce cas et son effet sur la résilience est quantifié. De plus, nous quantifions une construction servant à évaluer le risque pour le stock et la pêche. Les points de référence imposent un fardeau excessif aux pêcheurs ou aux défenseurs de l'environnement, et l'équilibre de ces risques dans une construction mathématique est présenté ici. Alors que 0,4 B_{PME} peut être une cible adéquate pour une limite, cela crée une erreur de type II élevée, c'est-à-dire l'absence de protection du stock si nécessaire pendant 80% du temps. Si l'on essaie de réduire ce risque, cela augmente le risque de perte de production lorsque cela n'est pas nécessaire. Une limite avoisinant 0,6 SSB_{PME} a été suggérée pour ce stock, afin d'équilibrer le risque entre la ressource et la pêche.

RESUMEN

Hasta hace poco, el pez espada del Atlántico norte ha sido pescado en una F/s elevada. Esta reducción en la presión pesquera ha recuperado las poblaciones y se ha difundido como un éxito en la ordenación de ICCAT. Sin embargo, las razones no se comprenden bien y hemos utilizado un enfoque matemático para estimar la inclinación basándonos en los datos y estudios sobre ciclo vital y posteriormente hemos usado dicha información a la hora de evaluar la resiliencia en el momento de recuperación a los puntos de referencia límite y objetivo para este stock. La inclinación es, implícitamente, un parámetro muy importante en esto y se cuantifica su efecto en la resiliencia. Además, hemos cuantificado una construcción para evaluar el riesgo para el stock y la pesquería. Los puntos de referencia colocan una carga indebida en los pescadores o los conservacionistas y se presenta el equilibrio de estos riesgos en una construcción matemática. Aunque 0,4 B_{RMS} podría ser un bien objetivo para un límite, crea un error alto tipo II, es decir, no protege el stock cuando es necesario durante el 80% del tiempo.

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Si intentamos reducir este riesgo, aumenta el riesgo de una pérdida en el rendimiento cuando no es requerido. Se sugiere un límite de aproximadamente 0,6 SSB_{RMS} para este stock, para equilibrar el riesgo entre el recurso y la pesquería.

KEYWORDS

Steepness, Resiliency, North Atlantic swordfish, Life history parameters

Introduction

North Atlantic swordfish (SWO_N) possess unique attributes and adaptations that contribute to resiliency (Neilson et al., 2013). The non-schooling behavior of swordfish may positively affect the survival of North Atlantic swordfish, since they are not subject to higher sources of fishing mortality from more efficient modes of capture (PS) that take advantage of schooling behavior. Another advantage swordfish may have, is its reproductive biology attributes like swordfish's broadcast spawning of many eggs in response to large-scale spatial and temporal patchiness in food supply or suitable habitats that spans over a broad spatial range and over a prolonged time in different habitats than its counterparts (*i.e.*, blue marlin and northern Bluefin tuna). The broadcast spawning displayed by North Atlantic swordfish over different areas of the North Atlantic along with its rapid growth rate, particularly at younger ages, contributing to a reduced natural mortality, and the reduction in fishing effort in important spawning grounds (likely USLL reduction in SW Sargasso Sea) may have contributed to the recovery of the stock.

In the last swordfish stock assessment, efforts were advanced on the use of a statistically integrated assessment model (SS) that would take into consideration a great number of different data necessary for a more comprehensive model (ICCAT, 2014). It was indicated that key parameters used in the model were dependent on the model configuration, and one of those very critical parameters was, and continue to be, steepness (Schirripa, 2014). Steepness, or resilience, of a stock-recruitment relationship measures the expected reduction in recruitment when spawning biomass declines to 20% of its unfished level. The poor understanding of the resilience (*i.e.*, steepness) of a stock-recruitment relationship, can be a source of primary uncertainty for determining stock status and biological reference points, and in many cases it is common to use a Bayesian approach to use plausible values of steepness in the absence of alternative information, as was the case in the statistical integrated model (SS) model used for hypothesis testing and corroboration purposes in the last Swordfish assessment (ICCAT, 2014). Thus, to address the uncertainty in the estimation of steepness, and in preparation for the 2017 stock assessment of the North Atlantic swordfish (SWO_N) SA, the individual-based simulation method form of Mangel et al. (2010) was used to characterize the probable distribution of steepness values under a Beverton–Holt stock-recruitment assumption. In the present document, the analyses used the complete information available on reproductive biology and life history parameters estimated for SWO_N, which included information on growth, average weight at length, maturity at age, batch fecundity, spawning frequency, duration of spawning season, egg weight, and early life history duration (Arocha, 1997, Arocha, 2007, Arocha et al., 2003).

In the present document, a mathematical approach is taken to estimate steepness based on life history data and studies, and then use that information in assessing resiliency in time of rebuilding to target and limit reference points for this stock.

Methods

Steepness parameter for the Beverton-Holt stock-recruitment relationship

Steepness was calculated from the slope at the origin as denoted by Mangel et al. (2010), Brodziak et al. (2015), and expressed as:

$$h = \frac{\alpha_S \cdot SPR_0}{4 + \alpha_S \cdot SPR_0}$$

In which steepness (h) is a function of the surviving spawning biomass per recruit in the absence of fishing (SPR_0) and the slope at the origin α_s . In the present document, the surviving spawning biomass per recruit in the absence of fishing (SPR_0) used was 241.82, obtained from the YPR curve from the last SWO SA (ICCAT, 2014)

The slope at the origin (α_s), as *per* Brodziak et al. (2015), is the product of larval survival and the spawning biomass, calculated by using life history data from SWO_north, and is expressed as:

$$\alpha_s = \frac{L_S \sum_j N_S \cdot E(W(a_j))}{\sum_j W(a_j)}$$

Where, L_S is larval survival to the expected weight at age-0 under a von Bertalanffy growth function; N_S is the number of spawning events (days); $E(W(a_j))$, expected egg production of a selected female in a single spawning event; $W(a)$ the weight of fish.

Data sources

Length-weight data was obtained from US and Venezuelan observer data collected between 1990 and 1997 (**Figure 1**), which consisted of sex-specific dressed weight (DWT) information for 14232 specimens (58-300 cm LJFL; 1-244 k DWT). The dressed weight (DWT) was converted to RWT using the relationship for the NW Atlantic in the ICCAT Manual (2006), to then estimate new sex-specific L-W parameters (a , b) for female and male SWO_n. The new estimated parameters ($a=8.757 \times 10^{-6}$, $b=3.0682$ for females; $a=7.162 \times 10^{-6}$, $b=3.1046$ for combined sex) for the L-W relationship was used to convert length to weight in all the analyses (**Table 1**).

Life history parameters for SWO_n were obtained and/or derived from Arocha (1997, 2007), Arocha et al. (2003), and Govoni et al., (2003). SWO_n growth was simulated with the VBG function estimated by Arocha et al. (2003), with female growth parameters of $L_\infty=312.3.0$ cm LJFL, $k=0.092$, and $t_0=-3.76$ (**Table 1**).

The median age at maturity (A_{50}) of a SWO_n female is 5.03 yrs, and full maturity (A_{100}) is 8.7 yrs; the reported average time between spawning events was 2.6 days characterized as the spawning frequency, and the defined spawning season was 7 months (212 days) from December to June (Arocha, 1997, 2007) (**Table 1**).

To estimate total egg production-at-age of a population, the fecundity-at-age relationship, the spawning frequency and the length of the spawning season were needed. The fecundity-at-age relationship estimated by Arocha (1997, 2007), that included an initial fecundity added to a power function was used.

To estimate the expected duration of early life history stages of eggs and larval fish to compute size-specific allometric natural mortality rates and associated survival probabilities of early life history stage females we followed the methods described in Brodziak et al (2015). It was assumed that early growth was exponential prior to the onset of a VBG pattern, which it was presumed that started at $L(0)$, which under the female VBG it was estimated as $L(0)=91.9$ cm LJFL. Therefore to estimate the expected duration of the early life history stage (D_{ELH}), the ratio of the estimated size realized at the end of early life history stage ($L(0)=91.9$) to the empirical size at age 1 ($L(1)=109.85$) observed by Arocha et al. (2003), times the number of days in a year (365) resulted in 305 days (D_{ELH}) (**Table 1**).

Early growth, expressed as the daily increase in the body mass of eggs and larvae, was modeled as an exponential function with a constant daily rate of increase in body mass (K_{ELH}) (*sensu* Brodziak et al., 2015). SWO_n larvae has a 2 phase growth (Govoni et al., 2003), its data was digitized and re-estimated as exponential growth ($r=0.846$) to accommodate to the above assumption. A *per* Brodziak et al. (2015), the expected body mass (wet weight) at an age of d days ($W_{ELH}(d)$) was computed from the initial egg weight to the ending age-0 weight as: $W_{ELH}(d) = W_E \cdot \exp(K_{ELH} \cdot d)$. Where $K_{ELH} = \log(W(0)/W_E)/D_{ELH}$ and W_E is egg weight. Thus, growth of early life history stages of SWO_n was determined by the initial egg weight ($W_E=6.17 \times 10^{-4}$ g), the mean weight at age corresponding to the mean length at age 0 from the VBG growth curve ($W(0)=9251.24$ g), and the duration of the early life history stages ($D_{ELH}=305$) (**Table 1**).

The estimation of survival rates of early stages followed the description of Brodziak et al., (2015), which were characterized assuming an allometric scaling of natural mortality as a decreasing function of body mass. But as indicated in Mangel et al., (2010), to compute the expected mass that an egg contributes to future biomass, the survival during the period before being recruited to the population was needed for the model; for this, we used McGurk's (1986) empirical relationship for estimating daily mortality rates during the early life history period (i.e., eggs and larvae): $M_{ELH}(d) = 0.00022 \cdot w_{ELH}(d)^{-0.85}$. Thus, the predicted daily natural mortality rate

($M_{ELH}(d)$) on the d^{th} day of life was an allometric function of dry weight body mass $w_{ELH}(d)$; where $w_{ELH}(d)=0.2 \cdot W_{ELH}(d)$ (**Table 1**).

Resiliency Quantification

The Dilemma of Low Spawning Biomass

In a managed fishery (fishery system), spawning biomass may drop to lower than desirable levels because:

- 1) Harvest rates have been higher than desirable thought;
- 2) Productivity, i.e. recruitment has been lower than estimated; or
- 3) Chance resulting from natural variation around a mean production (process error).

The appropriate management response to the first and second circumstances is the same: reduce harvest rates such as is the result from an Additional Management Action (AMA). The appropriate response to the third circumstance is to maintain a sustainable and well-estimated harvest rate, and in all three cases, invoke a rebuilding strategy (another essential piece of the MSE) through a set of Harvest Control Rules (HCR's).

A lower bound can be used as a threshold below which a high frequency of low Spawning Biomass would be an unlikely event, given what we know of harvest rates and productivity. If such an unlikely event occurs, we would conclude, more probably, that either harvest rates have been consistently higher than estimated, or productivity consistently lower than estimated. Our knowledge of fishing mortality rates and productivity are both based on parameters estimated with uncertainty, meaning that our knowledge may be faulty. Also, past productivity could have been accurately assessed, but current productivity of the stock may have declined due to changes in environment. Regardless of the circumstance, the logical response to unexpectedly low Spawning Biomass would be to lower harvest rates (implement AMA). Otherwise, the stock might suffer recruitment overfishing and be placed at higher risk of further declines in abundance.

One should note, however that low Spawning Biomass can and do occur from chance alone with no shift in productivity or average harvest rates. Restricting harvest under this circumstance would be unnecessary, pushing average Spawning Biomass above the level that produces maximum sustained yield (MSY) and the average yields below MSY, though using the precautionary principle (Richards and Maguire 1998) would not necessarily be bad for the fishery.

This dilemma defines the two types of risk associated with management based on Spawning Biomass. The first (Type I Risk) is the risk of unnecessarily restricting fishing-induced mortality when Spawning Biomass is below a threshold, that is, when chance alone has lowered Spawning Biomass, *i.e.*, in an easily reversible situation. The second (Type II Risk) is the risk of not restricting fishing-induced mortality even though productivity has declined irreversibly, but chance has kept Spawning Biomass above the threshold. Fortunately, the trade-off between these two types of risk can be quantified and used to set a rational lower bound using available information and reasonable intuition.

Estimating Risk

Estimating risk of management error through AMA begins with the probability that a stock “requires response” in a particular year. If probabilities of each event “requiring response” are independent over time (assumed when there is no evidence of dependence), the probability no “response” is needed is:

$$\text{Prob (No Stock “Requires Response”)} = 1 - p_i \quad \text{eq. 1}$$

Where, p_i is the probability that the stock (i) “requires response”. Therefore, the probability of AMA is the complement of the equation above: p_i eq. 2

Accordingly:

- 1) Type II Risk is zero and Type I Risk equals eq. 2 whenever a stock is not overfished; or
- 2) Type I Risk is zero and Type II Risk equals eq. 1 whenever a stock is overfished

If the p_i were known, risk would be known. However, risk of both types must be estimated because the p_i must be estimated for each set of conditions implicitly assuming a set harvest rate policy.

The probability p that a stock would meet the criterion of being overfished in a given year can be estimated with the simulation approach presented here. These simulations would:

- 1) Be based on an estimated stock-recruit relationship;
- 2) Be stochastic with variation in:
 - 2a) process error;
 - 2b) maturation and selectivity rates;
 - 2c) harvest rates; and
 - 2d) measurement error in estimates of future Spawning Biomass;

Note in the scenario developed, we are only varying process error, as maturation and selectivity rates are assumed constant over time, and harvest rate is varied and is a specified management control. Finally, in the simulation developed we assumed spawning biomass could be estimated perfectly. However stochastic variations within bounds could be introduced on all these variables.

- 3) Have an optimal harvest rate as estimated using stable state assumptions of the age structure of the stock;
- 4) Have 100000 iterations;
- 5) Be robust to initial conditions; and
- 6) Have a specific lower bound for future Spawning Biomass.

Average harvest rate in each simulation is set to the estimated optimal rate to be consistent with the management goal of MSY, which can be estimated using equilibrium assumptions. Influence of initial conditions on the simulations is reduced by disregarding results from earlier iterations (a "burn-in" period). Probability p_i is estimated from the remaining iterations (M "years" in the simulations) by dividing the number of years in which the criterion was met (m events that show the stock goes below a threshold) by M . While this calculation ignores that "years" in each simulation are not independent, this dependence should be inconsequential with large numbers of iterations. **Figure 2** is a graphical representation of the results of a series of such simulations of an optimally fished stock across a spectrum of lower bounds.

With one modification, simulations as described above can represent overfished stocks. If all other factors are as before, including the average harvest rate, overfishing can be simulated by reducing the density-independent parameter h in the estimated stock-recruit relationship. Remembering that overfishing occurs with a reduction in productivity, a reduction of κ (x100%) in productivity is represented as a change in eq.4:

$$N_{1,t} = \frac{\alpha S_{t-1}}{\beta + S_{t-1}} \quad \text{eq. 3}$$

Where

$$\alpha = \frac{4hR_0}{5h-1} \quad \text{eq. 4}$$

$$\text{and } \beta = \frac{B_0(1-h)}{5h-1} \quad \text{eq. 5}$$

Where h is steepness (base case $h=0.8$ was used in the simulations), R_0 and B_0 are recruitment at Virgin Biomass and Virgin Biomass respectively, α and β are parameters related to the density independent and dependent terms in the Beverton-Holt relationship.

Thus

$\alpha' = \frac{\kappa(4hR_0)}{5h-1}$ is used in simulations instead of α . In **Figure 2 (panel B)** shows the effect on of reducing productivity by 50% on an estimated relationship between π and a lower bound.

Note that for each lower bound and each stock there are two values of π . The first value, call it π' , is the probability of meeting the criterion (going below a threshold limit) under optimal fishing. The second value, call it π'' , is the probability of meeting the criterion with overfishing. In the example in **Figure 2 (panel B)**, overfishing represents a 50% reduction in estimated productivity, while simulated harvest rates remained at levels estimated to optimally harvest a stock with 100% of estimated productivity.

As independence is the assumption used to estimate the probability of an event, the chance of being below a threshold given you were below the threshold in the previous year is also p_i and having an event occur 2 years in a row is $(p_i)^2$. Normally such successive events are extremely low, and if we note this to happen, then the chances of overfishing are probably high.

Note quantifying Type I and Type-II errors at each level would eventually show a profile shown in **Figure 3**. Thus, the chance of making a Type II error when you take AMA when the reference point is high normally lower than when the reference point for the stock is low. In contrast, the type I error, *i.e.*, you take an unnecessary AMA when it wasn't required occurs when the reference point is high is higher than when it is low (Figure 3). These profiles are generated by running the models numerous times at different levels for reference points. In addition, the probability of a Type II error with a small drop in productivity is a lot higher than detecting a larger drop in productivity.

Simulation Model Used

A standard age-structured model was used:

$$N_{a+1,t+1} = N_{a,t}(1-u_t v_a) s_a \quad \text{for } a > 1, a < n \quad \text{eq. 6}$$

$$N_{n,t+1} = (N_{n,t} + N_{n-1,t})(1-u_t v_n) s_n \quad \text{for } a = n \quad \text{eq. 7}$$

$$E_t = \sum_a N_{a,t} f_a \quad \text{eq. 8}$$

$$N_{1,t+1} = g(E_t) \quad \text{eq. 9}$$

Where the functional forms are given in eq. 3, 4 and 5 above. The only difference is that process error is used, and has some auto-correlation built in it, so equation 9 is modified to:

$$N_{1,t+1} = g(E_t) e^\varepsilon \quad \text{where } \varepsilon \sim \sigma^2 N(0,1) \quad \text{eq. 10}$$

Auto-correlation in the process error term is defined as:

$$\varepsilon_t = \phi \varepsilon_{t-1} + (\sqrt{1-\phi^2}) \varepsilon_t \quad \text{where } \varepsilon_t \sim \sigma^2 N(0, \sigma^2) \quad \text{eq. 11}$$

$$C_t = \sum_a u_t v_a N_{a,t} w_a \quad \text{eq. 12}$$

Where:

- $N_{a,t}$ number of individual s age a time t
- u_t fraction harvested time t
- v_a vulnerability to fishing age a
- n oldest age considered
- s_a survival from natural mortality
- E_t spawning biomass time t
- f_a egg production age a
- g recruitment function (B/H, Ricker etc)
- C_t biomass of catch
- w_a mass at age a
- ϕ is the autocorrelation term, and can be between 0 and 1.

Results and discussion

Steepness (h) and quantities of new recruits per spawning biomass (α_s) were estimated using the life history estimates presented in **Table 2**. Several effects on the steepness (h) parameter were tested, among them were, the effect of estimated larval survival per day, versus the change in body mass per day and the steepness parameter, and the change in steepness when not all ages are used (**Figure 4**). In the first case, survival increases exponentially after 200 days when early growth shows signs of rapid growth, thus as natural mortality decreases, the increased in steepness is noticeable, changing from 0.86 initially to 0.98 at 200 days. In the second case, steepness appears highly sensitive when not selecting the full range of ages of the cohort, noting the value of using all ages, due to the high increase in egg production of older fish (>8 yrs). The change in steepness, as a function of spawning biomass per recruit in the absence of fishing (SPR_0) and new recruits per spawning biomass (α_s) is presented in **Figure 5**.

Life History Based parameter used for SWO_North

Figure 6 indicates the key parameters we used in developing the simulation to assess risk (Type I Error) using the framework described above. Using these parameters and a ϕ -0.3, we assess a stock which would show the following dynamics as presented in **Figure 7**.

Based on these parameters and these simulations we assessed the time it would take to recover to target (MSY) reference point by reducing the F by 33%. As such, target FMSY was around 0.26 with a yield around 16.6 Kt and SPB around 58kt (**Figure 8**).

Based on the dynamics of this population, we assess recovery time to target and limit reference points when fishing at a certain level (x axis/1st row of table) and auto-correlation on the 1st column of the table. Values in the table indicate the time it would take to recover to the limit with a cut in operational F (values indicated in table in the 1st row) by 33%.

So, this is the effect on time to recovery over limit using steepness of 0.9 as estimated through Mangel's et al. (2010) approach (**Table 3**), autocorrelation and F levels. The red values indicate longer recovery time as F targets are higher than FMSY levels and more autocorrelation in recruitment process (bad years followed by bad years versus good years followed by good years).

In the next table (**Table 4**), we evaluate the time to come back to the target FMSY and SB MSY for the stock. The stock is unlikely to recover if F targets are too high, as shown below (150+ years). Finally, the key point of how steepness relates to resiliency is shown in **Table 5**. This indicates that the stock is more susceptible to a higher probability of overfishing when steepness is low (0.7 or lower) than if it is around 0.95 (**Table 5**). Regardless if Target F's are too high there is a low chance of being above the limit. Essentially, if you want to play a conservative role, we should never target the stock to MSY levels of fishing pressure, especially if we don't know what steepness is. If we use the forms of steepness presented here, we would target a FMSY target of 0.9 of FMSY so we fish at 90% fishing mortality that achieves pretty good yield (a concept taken out by Hilborn et. al. (2010) in recent years), as we don't lose a lot in the yield of the stock, but gain a lot in long-term sustainability for the stock.

Conclusions

Based on these data and base case of 0.9 steepness with the life history parameters that are shown in Tables 1,2 and Figure 6; a new figure (**Figure 9**) is generated that indicates the type I and type II errors presented in methods. Based on Figure 9, it is apparent to see that if we drop the limit to below 0.2 S_{MSY} , we would threaten the resource by failing to protect it when a management action was needed if a 15% drop in productivity occurred. However, once we reach 0.8 S_{MSY} , the risk drops significantly, though now we adversely impact fisheries 60% of the time by taking a management action when it is not needed (**Figure 9**). Thus, we either over-protect the resource and penalize the fisheries or *vice versa*.

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Table 1. North Atlantic swordfish (SWO_North) life history parameters used to estimate steepness (h).

Description of life history parameters	Base case (females)
<i>Growth.</i> The asymptotic length parameter (L_∞) for the von Bertalanffy growth function-at-age, the growth coefficient parameter (k), and the value of age at length zero (t_0) parameter.	$l_t = L_\infty \left(1 - e^{-k(t-t_0)}\right)$ $L_\infty = 312.3 \text{ cm LJFL}$ $k = 0.0926$ $t_0 = -3.762$
<i>Length-weight.</i> The scale (A) and the exponent (b) parameters of the length-weight equation.	$RWT = A \cdot L^b$ $A = 0.000008757$ $b = 3.0682$
<i>Sexual Maturity.</i> The female age at 50% (A_{50}) and shape (α_M) parameters of the logistic function of maturity-at-age.	$M_f = \frac{1}{1 + e^{-\alpha_M(a_i - A_{50})}}$ $A_{50} = 5.03 \text{ yr}$ $\alpha_M = 1.24$
<i>Spawning and fecundity.</i> The average time between spawning events (T_B), the length of the spawning season (S_L), and relative fecundity (i.e., mean number of mature oocytes per gram of body weight, E_G).	$T_B = 2.6 \text{ days}$ $S_L = 7 \text{ months (Dec-Jun) } \sim 212 \text{ days}$ $E_G = 32.2 \text{ oocytes/g (13.2 - 61.9 oocytes/g)}$
<i>Early life history.</i> The early life history stage duration (D_{ELH}), and the mean egg weight (W_E).	$D_{ELH} = \frac{L(0)}{L(1)} \cdot 365$ $L(0) = 91.9 \text{ cm LJFL}$ $L(1) = 109.85 \text{ cm LJFL}$ $D_{ELH} \approx 305 \text{ days}$ $W_E = 6.17 \times 10^{-4} \text{ g}$
<i>Early growth.</i> Expected body mass at age of d days ($W_{ELH}(d)$).	$W_{ELH}(d) = W_E \cdot e^{(K_{ELH} \cdot d)}$ $K_{ELH}(d) = \frac{\log\left(\frac{W(0)}{W_E}\right)}{D_{ELH}}$ $W(0) = 9251.241 \text{ g}$ $K_{ELH}(d) = 0.02352 \text{ g}$
<i>Survival rates of early stages</i> (assuming an allometric scaling of natural mortality as a decreasing function of body). Daily natural mortality rate ($M_{ELH}(d)$) on the d th day of life was an allometric function of the dry weight body mass ($W_{ELH}(d)$).	$M_{ELH}(d) = b_0 \cdot w_{ELH}(d)^{b_1}$ $w_{ELH}(d) = 0.2W_{ELH}(d)$ <i>eggs & larvae (sensu McGurk, 1986):</i> $b_0 = 0.0002.2$ $b_1 = -0.85$
<i>Daily and Annual Natural Mortality.</i> The daily instantaneous natural mortality rates of eggs and larval fish ($M_{EL}(d)$), as well as instantaneous annual natural mortality at age for ages $a = 0, 1, \dots, A_{MAX}$.	<i>eggs & larvae:</i> $M_{ELH}(d) = 0.00022 \cdot w_{ELH}(d)^{-0.85}$

Table 2. Estimated parameters for the calculation of steepness (h) in SWO_n. Weight, maturity, and realized fecundity at age vectors; Egg production per body mass over the ages of the population; estimates of larval survival; and S_R parameter estimates.

<i>Age</i>	<i>RWT at Age</i>	<i>Maturity at age</i>	<i>Batch fecundity</i>	<i>Realized fecundity</i>
1	16.70	0.006		
2	26.31	0.023		
3	37.81	0.075	1894911.72	370611.79
4	50.86	0.218	1894911.72	1077634.78
5	65.17	0.490	1981856.518	2528652.24
6	80.35	0.768	2161089.745	4317132.83
7	96.12	0.919	2488937.996	5949991.26
8	112.25	0.975	3039353.041	7706172.37
9	128.38	0.992	3905735.925	10080366.77
10	144.41	1.00	5202667.656	13497933.7
11	160.16	1.00	7067562.331	18364197.7
12	175.49	1.00	9662254.378	25117305.62
13	190.28	1.00	13174528.86	34251970.01
14	204.50	1.00	17819601.84	46330255.4
15	218.03	1.00	23841556.38	61987770.84
16	230.91	1.00	31514738.98	81938215.44
<i>Sum_ W</i>	1937.78		<i>Sum_ E</i>	313518210.8
Length of spawning season (SL, days)	212			
Early Survival				
Expected body mass at D day (100 day) $W_{ELH}(d)$	$W_{ELH}(d) = W_E \cdot e^{(K_{ELH} \cdot d)}$		0.001297547	
Eggs and larvae Mortality at day, (d=100 day)	$M_{ELH}(d) = 0.00022 \cdot W_{ELH}(d)^{-0.85}$		5.69568E-09	
Estimated S_R parameters				
α_s	Estimate of new recruits per spawning biomass		0.195446903	
h	Steepness		0.92	
SPR_0	The expected surviving spawning biomass per recruit in the absence of fishing		241.82	

Table 3. Number of years it takes for Swordfish to recover to the limit when being fished at rates that are relative to FMSY levels an auto correlation coefficient on y-axis with a 33% reduction in fishing pressure.

		F/FMSY					
		0.5	0.9	1.4	1.8	2.3	2.7
Autocorrelation	0.1	0.0	0.0	1.3	1.8	2.9	5.9
	0.15	0.0	0.0	1.4	1.9	3.0	6.0
	0.2	0.0	0.0	1.5	2.0	3.2	6.1
	0.25	0.0	0.0	1.6	2.1	3.3	6.2
	0.3	0.0	0.0	1.8	2.2	3.4	6.3
	0.35	0.0	0.0	1.8	2.4	3.6	6.4
	0.4	0.0	0.0	1.9	2.5	3.8	6.6
	0.45	0.0	1.0	2.0	2.6	3.9	6.9
	0.5	0.0	1.5	2.1	2.8	4.1	7.0
	0.55	0.0	1.5	2.3	3.0	4.2	7.2
	0.6	0.0	1.9	2.6	3.2	4.5	7.3
	0.65	0.0	1.9	2.8	3.4	4.8	7.5
	0.7	0.0	2.2	3.0	3.6	5.0	7.8
	0.75	0.0	2.5	3.4	3.9	5.3	8.0
	0.8	0.0	3.0	3.7	4.3	5.5	8.3
0.85	2.0	4.0	4.0	4.7	5.7	9.1	
0.9	9.5	4.9	4.4	4.9	6.0	9.4	

Table 4. Number of years it takes stock to exceed targets when fished below the limit based on rates relative to FMSY on the x column and autocorrelation coefficient on y axis.

		F/FMSY					
		0.5	0.9	1.4	1.8	2.3	2.7
Autocorrelation	0.1	0	0	56	138	150	150
	0.15	0	0	47	136	150	150
	0.2	0	0	44	134	150	150
	0.25	0	0	46	132	150	150
	0.3	0	0	47	132	150	150
	0.35	0	0	44	132	150	150
	0.4	0	0	45	125	150	150
	0.45	0	9	51	117	150	150
	0.5	0	20	51	112	150	150
	0.55	0	26	51	109	150	150
	0.6	0	17	52	108	150	150
	0.65	0	14	53	106	150	150
	0.7	0	14	52	102	150	150
	0.75	0	15	55	101	146	150
	0.8	0	18	58	107	146	150
0.85	8	20	61	112	146	150	
0.9	25	34	70	119	150	150	

Table 5. Probability of going below a threshold as a function of steepness shown on y axis and fishing rates relative to FMSY. Limits are 0.4 BMSY which is around 15k SPB based on dynamic yield curves.

		F/FMSY					
		0.5	0.9	1.4	1.8	2.3	2.7
Steepness	0.6	0.00	0.00	0.36	0.84	0.99	1.00
	0.65	0.00	0.00	0.21	0.71	0.94	1.00
	0.7	0.00	0.00	0.11	0.57	0.87	0.98
	0.75	0.00	0.00	0.05	0.43	0.78	0.94
	0.8	0.00	0.00	0.03	0.31	0.68	0.88
	0.85	0.00	0.00	0.01	0.22	0.58	0.82
	0.9	0.00	0.00	0.01	0.14	0.47	0.73
	0.95	0.00	0.00	0.00	0.09	0.37	0.65

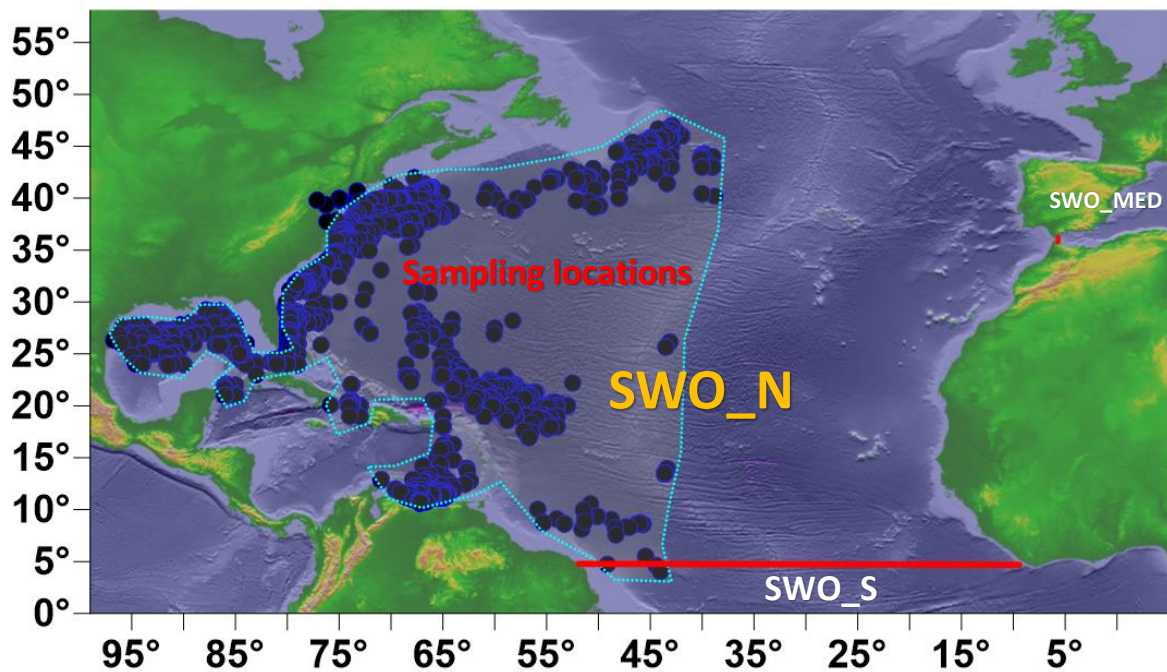


Figure 1. Locations of swordfish collected samples for life history parameters used in the present document, between 1990 and 1997 from scientific observer programs of US and Venezuela.

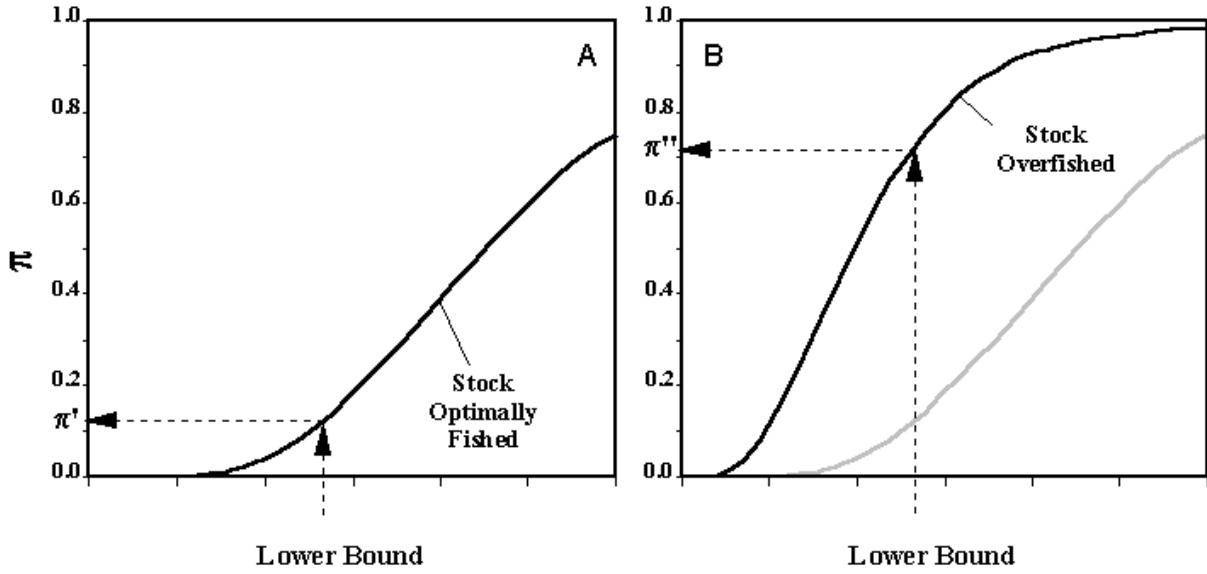


Figure 2. Estimated probability π of a stock meeting the threshold criterion in a particular calendar year as a function of a lower bound in Spawning Biomass under optimal fishing (Panel A) and under overfishing (Panel B) in which productivity has been reduced 50%. Curves are based on interpolations from individual simulations.

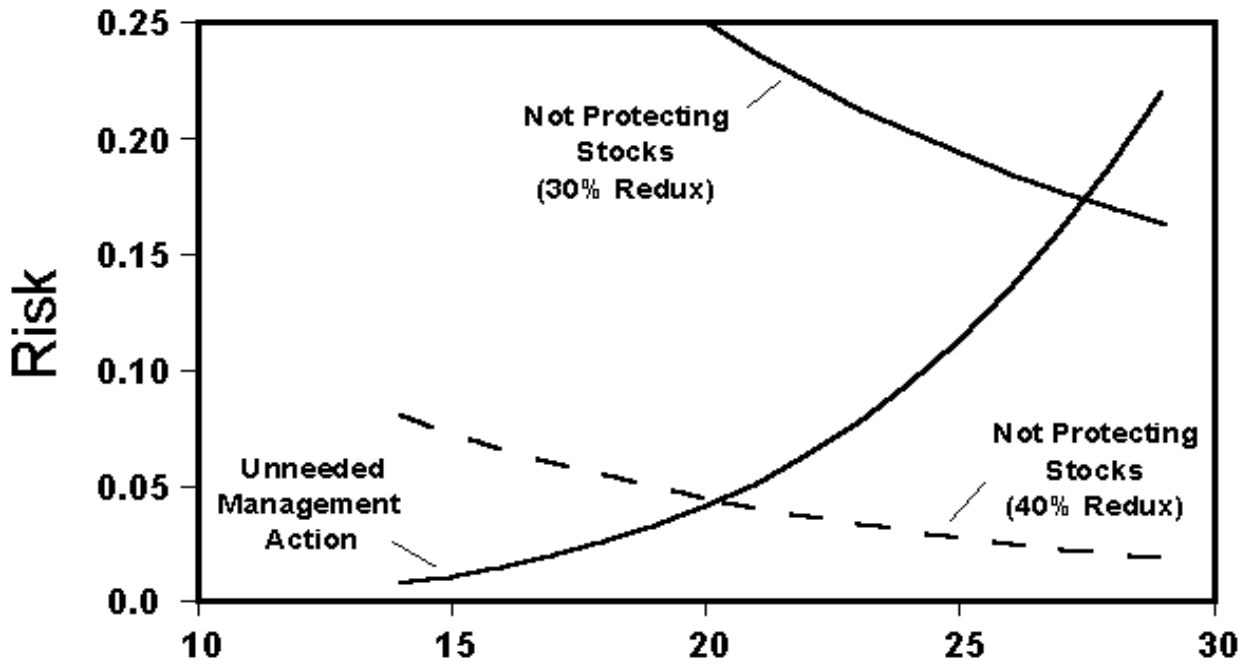


Figure 3. Type I and type II errors as a function of stock size for a theoretical population and estimated drops of 30 and 40% in productivity respectively.

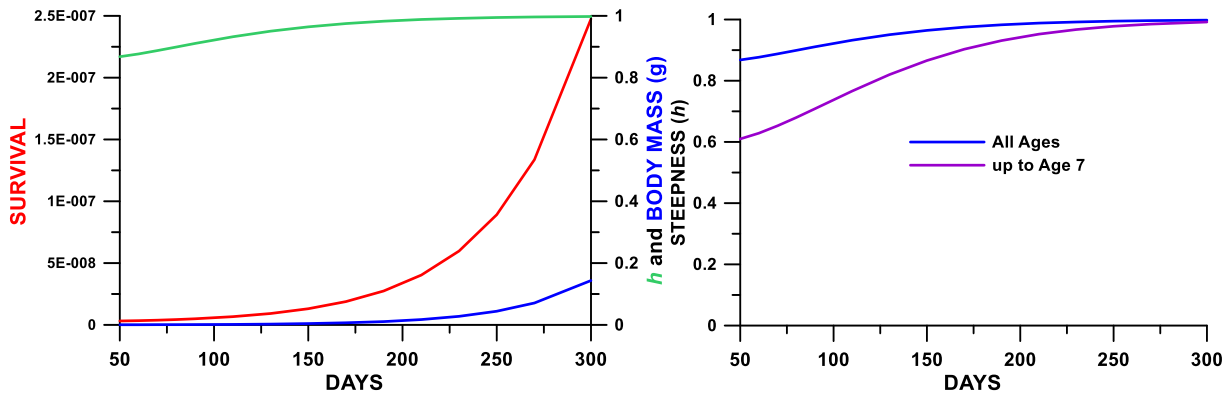


Figure 4. Effect of estimated larval survival per day, versus the change in body mass per day and the steepness parameter (h). Change in Steepness when not all ages are used. Noting the value of using all ages, due to the high increase in egg production of older fish.

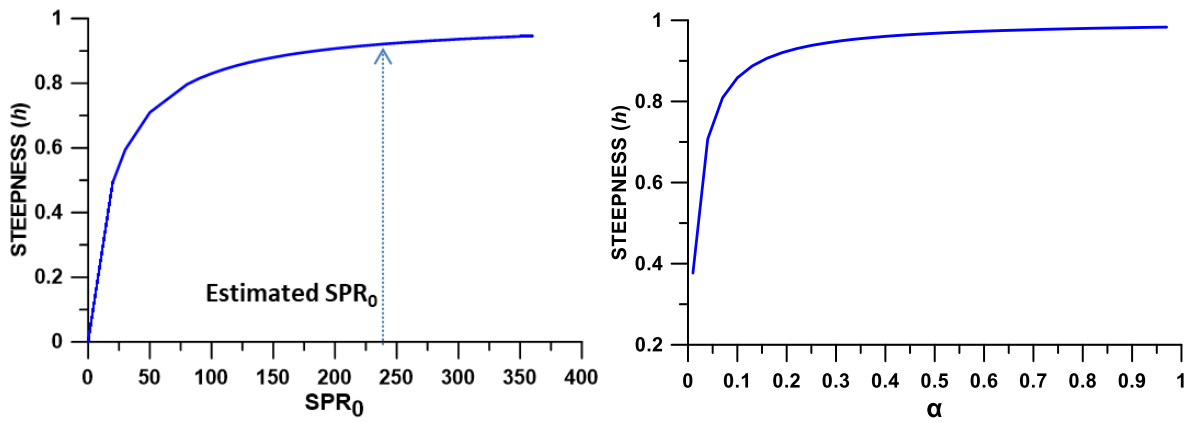


Figure 5. Changes in steepness as a function of the main parameters in the estimation of h , i.e., virgin biomass (SPR_0) and slope at the origin (α_s).

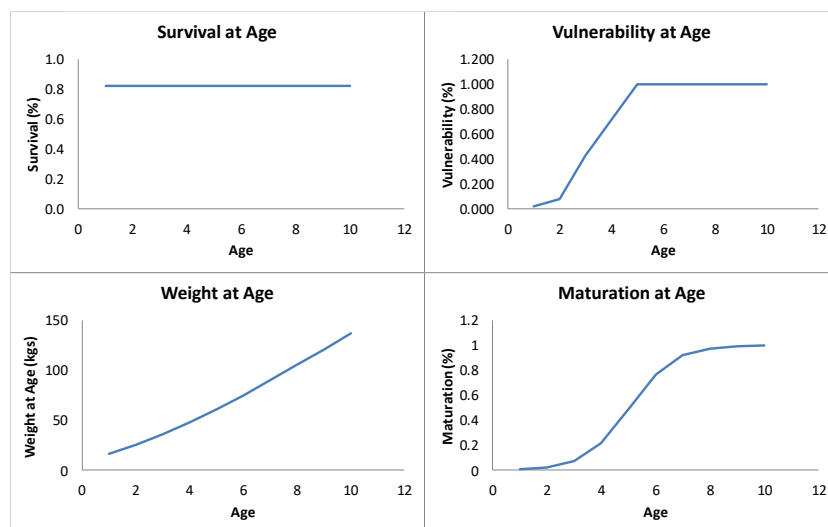


Figure 6. Life history based parameters (Survival/Natural M at age, vulnerability at age, weight at age, and maturation at age, used in simulation to assess risk.

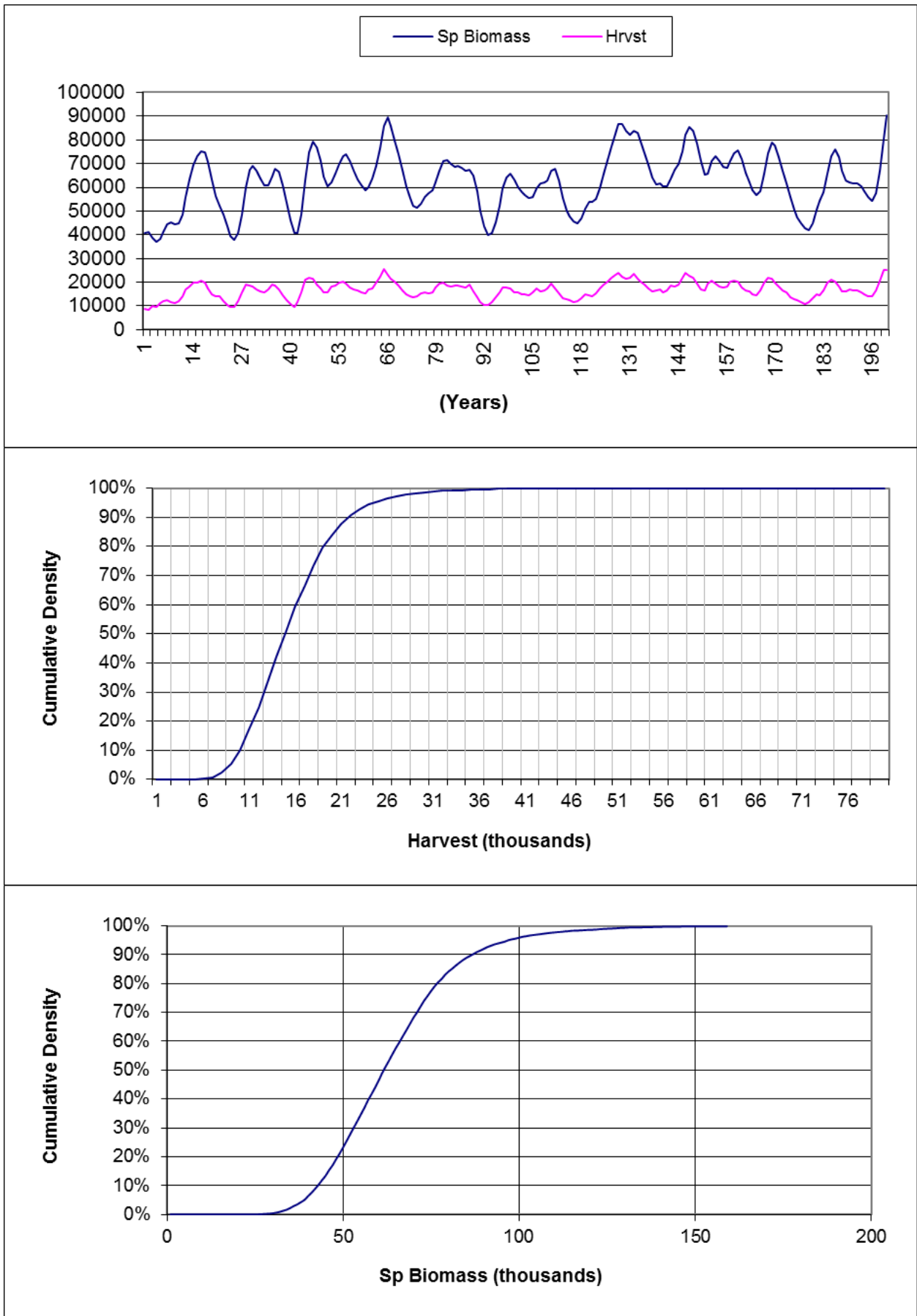


Figure 7. Dynamics of population trajectory and Risk (Type I error) for the stock is shown in the last panel of the figure, showing spawning Biomass Trajectories.

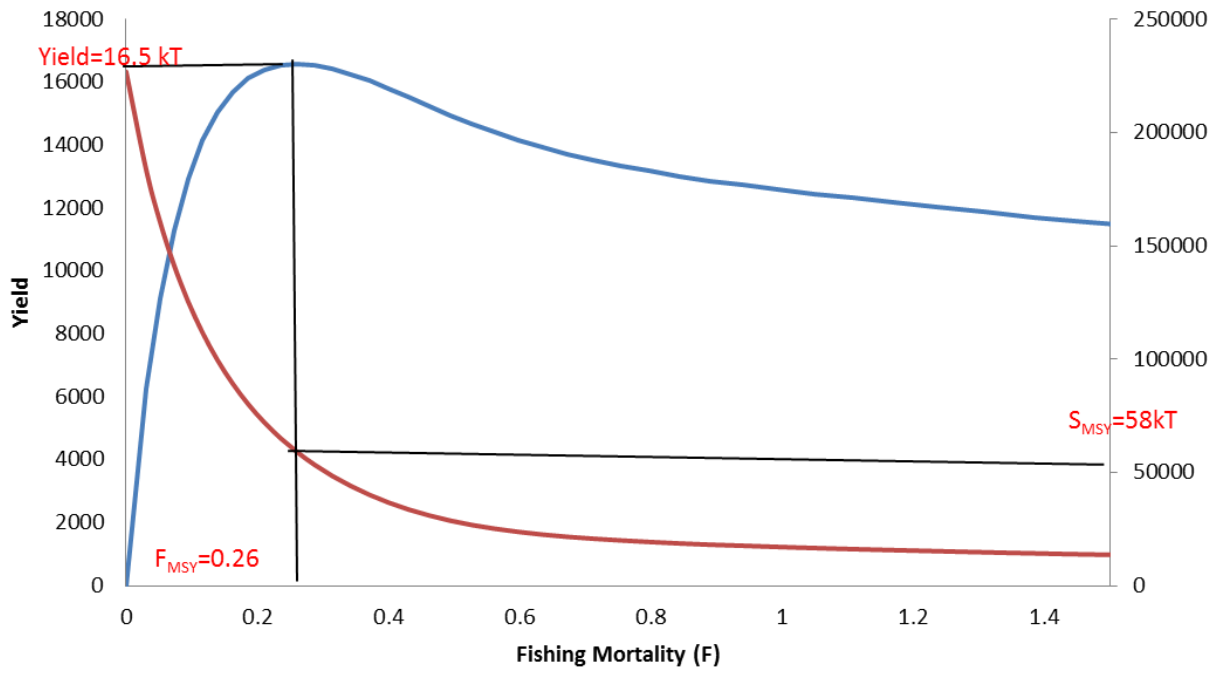


Figure 8. Dynamic yield using life-history parameters for Swordfish.

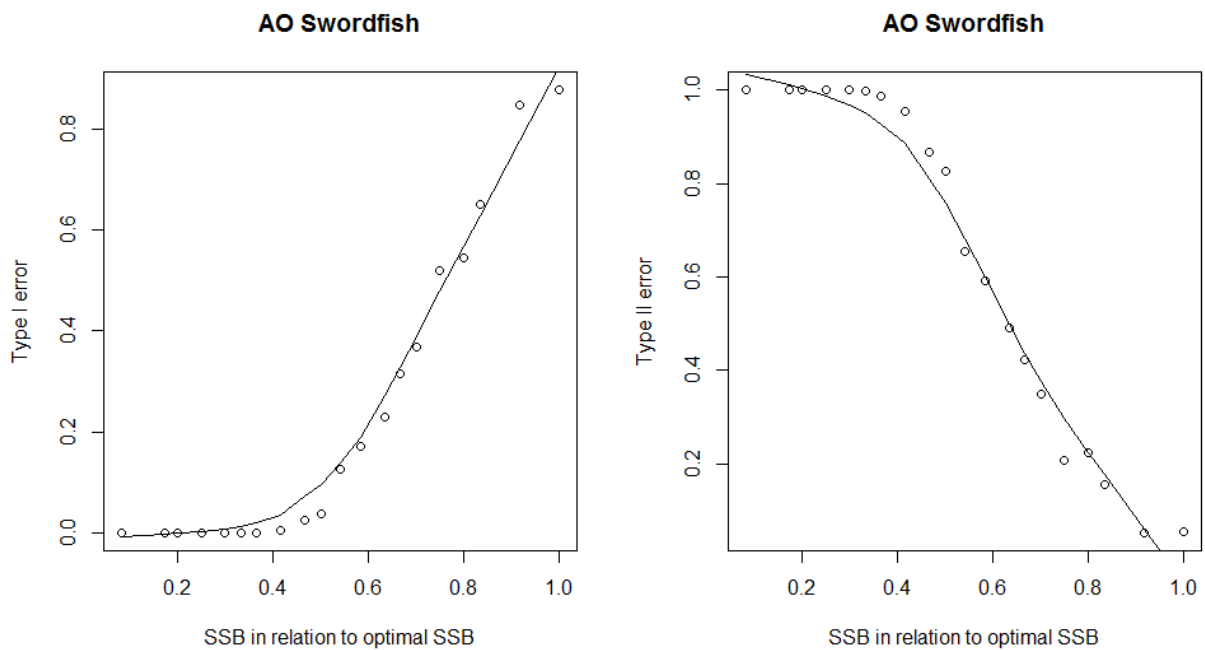


Figure 9. Type I and Type II errors quantified for the SWO_north population used in the simulations.