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# STOCK ASSESSMENT AND FUTURE PROJECTIONS OF BLUE SHARK IN THE NORTH PACIFIC OCEAN

**WCPFC-SC9-2013/ SA-WP-11**

**ISC SHARK WORKING GROUP[1]**

[1] International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean

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Shark Working Group

International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean

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## EXECUTIVE SUMMARY

### 1. Stock Identification and Distribution

Blue shark (*Prionace glauca*) in the Pacific is recognized by the ISC Shark Working Group (SHARKWG) as two stocks centered in the temperate and subtropical waters of the North and South Pacific, respectively. Relatively few blue sharks (BSH) are encountered in the tropical equatorial waters separating the two stocks. Tagging data demonstrate long distance movements and a high degree of mixing of BSH across the North Pacific, although there is evidence of spatial and temporal structure by size and sex.

### 2. Catch History

Catch records for BSH in the North Pacific are scant and, where lacking, have been estimated using statistical models and information from a combination of historical landings data, fishery logbooks, observer records and research surveys. In this assessment, estimated BSH catch data refer to total dead removals, which includes retained catch and dead discards. Estimated catch data in the North Pacific date back to 1971, although longline and driftnet fisheries targeting tunas and billfish earlier in the 20th century likely caught BSH. The nations catching BSH in the North Pacific include Japan, Chinese Taipei, Mexico, and USA which account for more than 95% of the estimated catch (Figure 1E). Estimated catches of BSH were highest from 1976 to 1989 with a peak estimated catch of approximately 90,000 mt in 1981. Over the past decade, BSH estimated catches in the North Pacific have remained steady at roughly 40,000 mt annually (Figure 1E). While a variety of fishing gears catch BSH, most are caught in longline and gillnet fisheries (Figure 2E). The total catch in 2011 decreased by close to 25% due to a decrease in Japanese effort associated with damage from the March 2011 Great East Japan Earthquake.

### 3. Data and Assessment

Stock biomass and fishing mortality levels were estimated using a state-space Bayesian surplus production model (BSP2[1]) that fit estimated catch to standardized catch-per-unit of effort (CPUE) data compiled by the SHARKWG from 1971 through 2011. Annual catch estimates were derived for a variety of fisheries by nation and compiled into a single catch time series for input into the BSP2 model. The SHARKWG developed annual estimates of standardized CPUE for several fisheries and used criteria to select representative indices for the assessment.

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[1] McAllister MK, Babcock EA (2006) Bayesian Surplus Production model with the Sampling Importance Resampling algorithm (BSP): a user's guide.

Standardized CPUE from the Japanese shallow longline fleet that operates out of Hokkaido and Tohoku ports for the periods 1976-1993 and 1994-2010 were used as measures of relative population abundance in the base case assessment (Figure 3E). A Fletcher-Schaefer production model was fit in a likelihood-based statistical framework with priors assigned to several parameters, including the intrinsic rate of population increase ($r$) and the ratio of initial biomass to carrying capacity ($B_{init}/K$). Bayesian posteriors of model parameters and derived outputs from the base case model were used to characterize stock status.

The SHARKWG recognized uncertainties in the procedures used to estimate catch and standardized CPUE series, and in the selection of input parameters and priors. The influence of these uncertainties on biomass trends and the 2011 fishing mortality level was assessed by constructing 21 sensitivity scenarios, which were designed to capture the maximum range of uncertainty in the input information, using alternative data and/or parameterizations.

Stock projections of biomass and catch of BSH in the North Pacific from 2012 to 2031 were conducted assuming 21 alternative harvest scenarios and starting biomass levels. *Status quo* catch and $F$ were based on the average over the recent 5 years (2006-2010). Estimated catch from 2011 was not used for projections due to the impact of the March 2011 Great East Japan Earthquake on Japanese fishing effort. A simulation model was used for annual projections, and included uncertainty in the population size at the starting year of stock projection, fishing mortality and productivity parameters.

**4. Status of the Stock**

Model inputs for this assessment have been improved since the previous assessment and provide the best available scientific information. However, there are uncertainties in the time series for estimated catch and abundance indices for BSH in the North Pacific, as well as for many life history parameters used to estimate stock productivity. Available catch composition information demonstrates evidence of spatial and temporal stratification by size and sex, which suggests that use of other modeling approaches, if sufficient data are available, may provide additional insights into stock dynamics. Improvements in the monitoring of BSH catches, including recording the size and sex of sharks retained and discarded for all fisheries, as well as continued research into the biology and ecology of BSH in the North Pacific are recommended.

Based on the trajectory of the base case model, median stock biomass of blue shark in 2011 ($B_{2011}$) was estimated to be 456,000 mt (Figure 4E). Median annual fishing mortality in 2011 ($F_{2011}$) was 7.14% of $B_{2011}$. Catch in 2011 ($C_{2011}$) was estimated to be 75% of replacement yield

(*REPY*). Stock status is reported in relation to maximum sustainable yield (*MSY*). Stock biomass in 2011 was approximately 60% higher than $B_{msy}$ and $F_{2011}$ was estimated to be well below $F_{msy}$ (Table 1E; Figure 5E).

While the results varied depending upon the input assumptions, there was general agreement in nearly all scenarios in terms of the key model results: stock biomass was near a time-series high in 1971, fell to its lowest level in the late 1980s, and subsequently increased gradually and has leveled off at a biomass similar to that at the beginning of the time-series (Figure 6E). A single scenario using CPUE data for the Hawaii-based deep longline fleet for 1995-2011 in place of the Japan shallow longline index for 1994-2010, showed a continual decline in stock biomass from 1971 to 2011. However, the Hawaii index was not considered to be representative of the stock due to the relatively small amount of catch and spatial coverage and the potential impact of regulatory changes in the fishery.

**5. Conservation Information**

The Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC) are responsible for management of pelagic sharks caught in international fisheries for tuna and tuna-like species in the Pacific Ocean.

Based on the base case and plausible model scenarios, the north Pacific blue shark stock is not overfished and overfishing is not occurring. Due to data uncertainties, improvements in the monitoring of blue shark catches and discards, as well as continued research into the biology and ecology of blue shark in the North Pacific are recommended.

Future projections of the base case model show that median BSH biomass in the North Pacific will remain above $B_{msy}$ under the catch harvest policies examined (status quo, +20%, -20%). Similarly, future projections under different fishing mortality (*F*) harvest policies (status quo, +20%, -20%) show that median BSH biomass in the North Pacific will remain above $B_{msy}$ (Table 2E; Figure 7E).

Projections under different catch and fishing mortality policies were also conducted for the maximum and minimum catch model scenarios. In all cases, patterns of trajectories were essentially the same as for the base case, and the projected stock biomass remained above $B_{msy}$. Projected stock biomass was lower for runs with either catch or *F* 20% above current, as expected, but remained above $B_{msy}$ (Table 2E).

The analyses indicate that the stock is in a healthy condition and current levels of $F$ are sustainable in the short and long term.

Table 1E. Base case model results of blue shark (*Prionace glauca*) assessment - median and 90% confidence intervals of important biological parameters and reference points. *REPY* and $C_{2011}$ indicates replacement yield and catch in 2011, respectively.

| Variable | 5th Percentile | Median | 95th Percentile |
|---|---|---|---|
| $r$ | 0.25 | 0.40 | 0.58 |
| $K$ (‘000 t) | 432 | 613 | 961 |
| $MSY$ (‘000 t) | 52 | 58 | 65 |
| $B_{MSY}$ (‘000 t) | 203 | 288 | 452 |
| $B_{1971}$ (‘000 t) | 208 | 393 | 732 |
| $B_{2011}$ (‘000 t) | 323 | 456 | 741 |
| $B_{2011}/B_{MSY}$ | 1.30 | 1.59 | 1.88 |
| $B_{2011}/B_{1971}$ | 0.81 | 1.17 | 1.94 |
| $B_{2011}/K$ | 0.65 | 0.80 | 0.94 |
| $F_{MSY}$ (%) | 12.6 | 20.0 | 29.0 |
| $F_{2011}$ (%) | 4.4 | 7.1 | 10.0 |
| $F_{2011}/F_{MSY}$ | 0.28 | 0.35 | 0.48 |
| $REPY$ (‘000 t) | 28 | 43 | 53 |
| $C_{2011}/REPY$ | 0.59 | 0.75 | 1.08 |

Table 2E. Decision table showing the expected catch and biological reference points for runs projecting 5, 10, and 20 years into the future, under different harvest policies with either constant catch or fishing mortality (status quo: $C_{2006\text{-}2010}$; $C_{2006\text{-}2010}$ +20%; $C_{2006\text{-}2010}$ -20%; $F_{2006\text{-}2010}$; $F_{2006\text{-}2010}$ +20%; $F_{2006\text{-}2010}$ -20%; and $F_{msy}$), based on future projections for the base case, and minimum and maximum catch models.

| Run ID | HCR | Total $C_{2011}$ | $B_{2011}/B_{msy}$ | $F_{2011}/F_{msy}$ | $C_{2011}$/RepY | Total $C_{2016}$ | $B_{2016}/B_{msy}$ | P($B_{2016}>B_{msy}$) | $F_{2016}/F_{msy}$ | $C_{2016}$/RepY | Total $C_{2021}$ | $B_{2021}/B_{msy}$ | P($B_{2021}>B_{msy}$) | $F_{2021}/F_{msy}$ | $C_{2021}$/RepY | Total $C_{2031}$ | $B_{2031}/B_{msy}$ | P($B_{2031}>B_{msy}$) | $F_{2031}/F_{msy}$ | $C_{2031}$/RepY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Base** | **Status quo** | 32.54 | 1.59 | 0.35 | 0.75 | 40.64 | 1.55 | 1.00 | 0.45 | 0.93 | 40.64 | 1.59 | 1.00 | 0.45 | 0.94 | 40.64 | 1.58 | 0.99 | 0.44 | 0.95 |
| | **+20%** | 32.54 | 1.59 | 0.35 | 0.75 | 48.77 | 1.45 | 0.99 | 0.58 | 1.05 | 48.77 | 1.44 | 0.96 | 0.59 | 1.01 | 48.77 | 1.42 | 0.95 | 0.60 | 0.99 |
| | **-20%** | 32.54 | 1.59 | 0.35 | 0.75 | 32.51 | 1.65 | 1.00 | 0.34 | 0.79 | 32.51 | 1.71 | 1.00 | 0.33 | 0.84 | 32.51 | 1.72 | 1.00 | 0.33 | 0.83 |
| | $F_{2006\text{-}2010}$ | 32.54 | 1.59 | 0.46 | 0.75 | 38.45 | 1.55 | 1.00 | 0.46 | 0.91 | 40.00 | 1.57 | 0.99 | 0.46 | 1.03 | 42.92 | 1.55 | 0.99 | 0.46 | 1.37 |
| | **+20%** | 32.54 | 1.59 | 0.56 | 0.75 | 43.99 | 1.46 | 0.99 | 0.56 | 0.96 | 45.30 | 1.47 | 0.97 | 0.56 | 1.04 | 48.45 | 1.44 | 0.96 | 0.56 | 1.28 |
| | **-20%** | 32.54 | 1.59 | 0.37 | 0.75 | 32.24 | 1.63 | 1.00 | 0.37 | 0.85 | 33.84 | 1.68 | 1.00 | 0.37 | 1.03 | 36.42 | 1.65 | 1.00 | 0.37 | 1.54 |
| | $F_{msy}$ | 32.54 | 1.59 | 0.35 | 0.75 | 66.38 | 1.12 | na | 1.03 | 1.17 | 60.44 | 1.04 | na | 1.01 | 1.05 | 57.97 | 1.00 | na | 1.00 | 1.00 |
| **MaxCat1** | **Status quo** | 47.71 | 1.49 | 0.53 | 1.01 | 45.25 | 1.51 | 0.99 | 0.49 | 0.95 | 45.25 | 1.50 | 0.99 | 0.49 | 0.95 | 45.25 | 1.54 | 0.99 | 0.48 | 0.96 |
| | **+20%** | 47.71 | 1.49 | 0.53 | 1.01 | 54.30 | 1.41 | 0.97 | 0.64 | 1.06 | 54.30 | 1.34 | 0.88 | 0.66 | 1.02 | 54.30 | 1.34 | 0.89 | 0.67 | 1.01 |
| | **-20%** | 47.71 | 1.49 | 0.53 | 1.01 | 36.20 | 1.63 | 1.00 | 0.37 | 0.81 | 36.20 | 1.64 | 1.00 | 0.36 | 0.84 | 36.20 | 1.68 | 1.00 | 0.35 | 0.89 |
| | $F_{2006\text{-}2010}$ | 47.71 | 1.49 | 0.51 | 1.01 | 42.21 | 1.50 | 0.99 | 0.51 | 0.86 | 36.62 | 1.48 | 0.98 | 0.51 | 0.67 | 44.05 | 1.50 | 0.98 | 0.51 | 0.95 |
| | **+20%** | 47.71 | 1.49 | 0.61 | 1.01 | 47.83 | 1.41 | 0.98 | 0.61 | 0.93 | 40.46 | 1.37 | 0.96 | 0.61 | 0.72 | 48.78 | 1.39 | 0.94 | 0.61 | 0.96 |
| | **-20%** | 47.71 | 1.49 | 0.41 | 1.01 | 35.73 | 1.59 | 0.99 | 0.41 | 0.78 | 31.72 | 1.59 | 1.00 | 0.41 | 0.61 | 38.01 | 1.62 | 0.99 | 0.41 | 0.93 |
| | $F_{msy}$ | 47.71 | 1.49 | 0.53 | 1.01 | 68.61 | 1.10 | na | 1.03 | 1.14 | 62.18 | 1.01 | na | 1.02 | 1.03 | 60.88 | 1.01 | na | 1.00 | 1.02 |
| **MinCat1** | **Status quo** | 23.85 | 1.56 | 0.41 | 0.85 | 27.99 | 1.54 | 0.99 | 0.50 | 0.98 | 27.99 | 1.54 | 0.99 | 0.49 | 0.95 | 27.99 | 1.51 | 0.99 | 0.51 | 0.95 |
| | **+20%** | 23.85 | 1.56 | 0.41 | 0.85 | 33.59 | 1.43 | 0.98 | 0.64 | 1.08 | 33.59 | 1.36 | 0.94 | 0.67 | 1.03 | 33.59 | 1.30 | 0.84 | 0.70 | 1.02 |
| | **-20%** | 23.85 | 1.56 | 0.41 | 0.85 | 22.39 | 1.64 | 1.00 | 0.37 | 0.84 | 22.39 | 1.68 | 1.00 | 0.36 | 0.85 | 22.39 | 1.68 | 1.00 | 0.37 | 0.84 |
| | $F_{2006\text{-}2010}$ | 23.85 | 1.56 | 0.50 | 0.85 | 28.24 | 1.51 | 1.00 | 0.50 | 0.83 | 30.47 | 1.53 | 0.99 | 0.50 | 0.96 | 28.75 | 1.51 | 0.98 | 0.50 | 0.85 |
| | **+20%** | 23.85 | 1.56 | 0.60 | 0.85 | 31.95 | 1.43 | 0.99 | 0.60 | 0.90 | 33.60 | 1.42 | 0.96 | 0.60 | 0.98 | 31.38 | 1.40 | 0.94 | 0.60 | 0.88 |
| | **-20%** | 23.85 | 1.56 | 0.40 | 0.85 | 23.93 | 1.61 | 1.00 | 0.40 | 0.74 | 26.45 | 1.65 | 1.00 | 0.40 | 0.94 | 25.14 | 1.62 | 1.00 | 0.40 | 0.82 |
| | $F_{msy}$ | 23.85 | 1.56 | 0.41 | 0.85 | 42.33 | 1.11 | na | 1.03 | 1.17 | 38.13 | 1.04 | na | 1.01 | 1.04 | 36.65 | 1.00 | na | 1.00 | 1.00 |

Figure 1E. Total estimated catch of north Pacific blue shark (*Prionace glauca*) from 1971-2011 by nation or region.

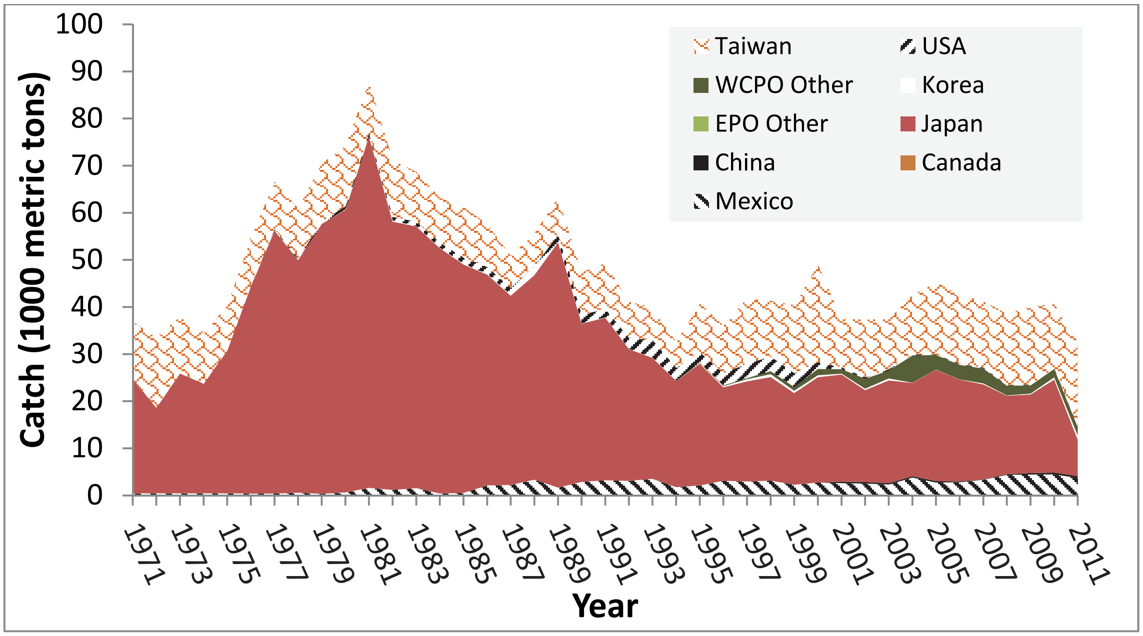



Figure 2E. Total estimated catch of north Pacific blue shark (*Prionace glauca*) by gear types from 1971-2011. Mixed gear reflects some combined longline, gillnet, pole and line, trap, purse seine.

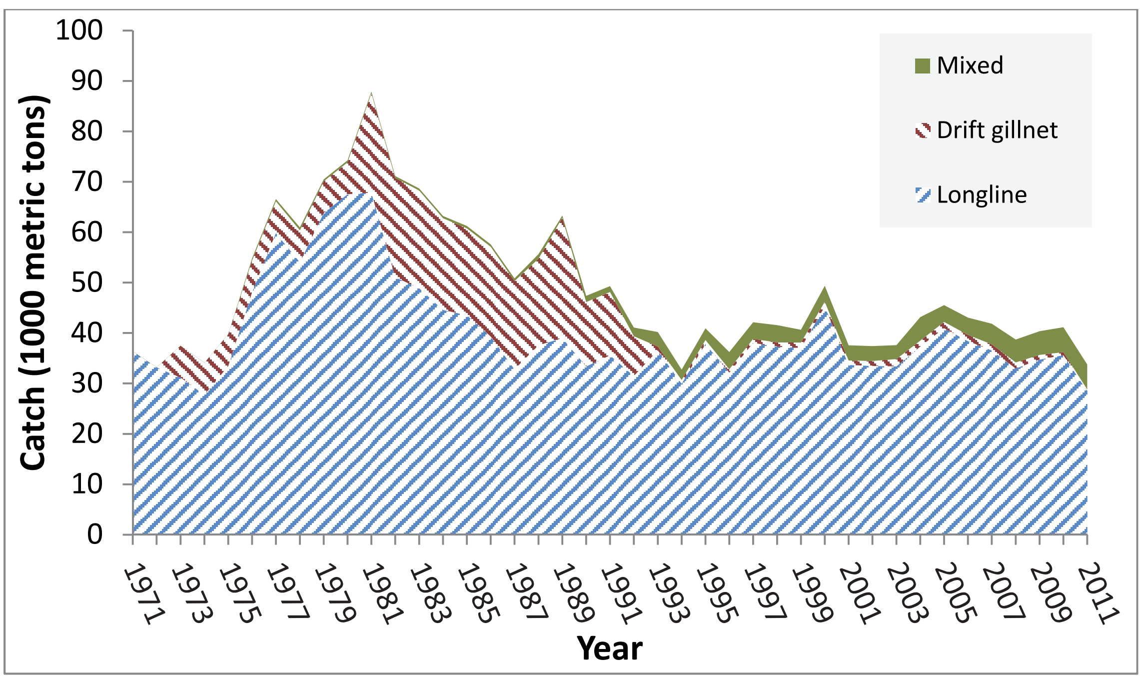


Figure 3E. Standardized CPUEs used as abundance indices in the blue shark (*Prionace glauca*) stock assessment. The base case model was fitted to the Japanese longline early (1976-1993), and late indices (1994-2010). A sensitivity run was fitted to the Hawaii deep-set longline index (1995-2011) and the Japanese longline early index to examine the effect of an alternative index for the late period.

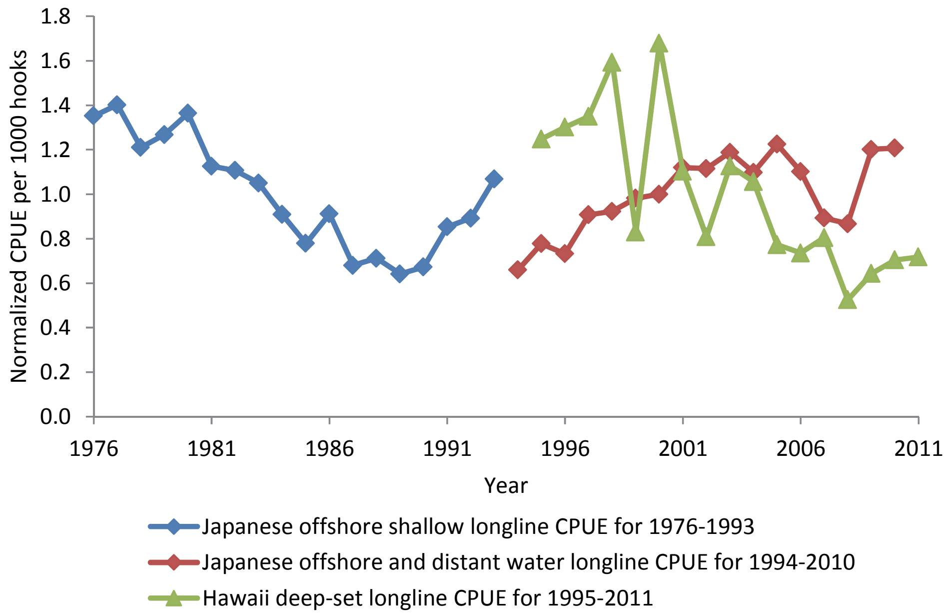



Figure 4E. Median and 90% confidence intervals for the estimated historical stock dynamics of north Pacific blue shark (*Prionace glauca*).

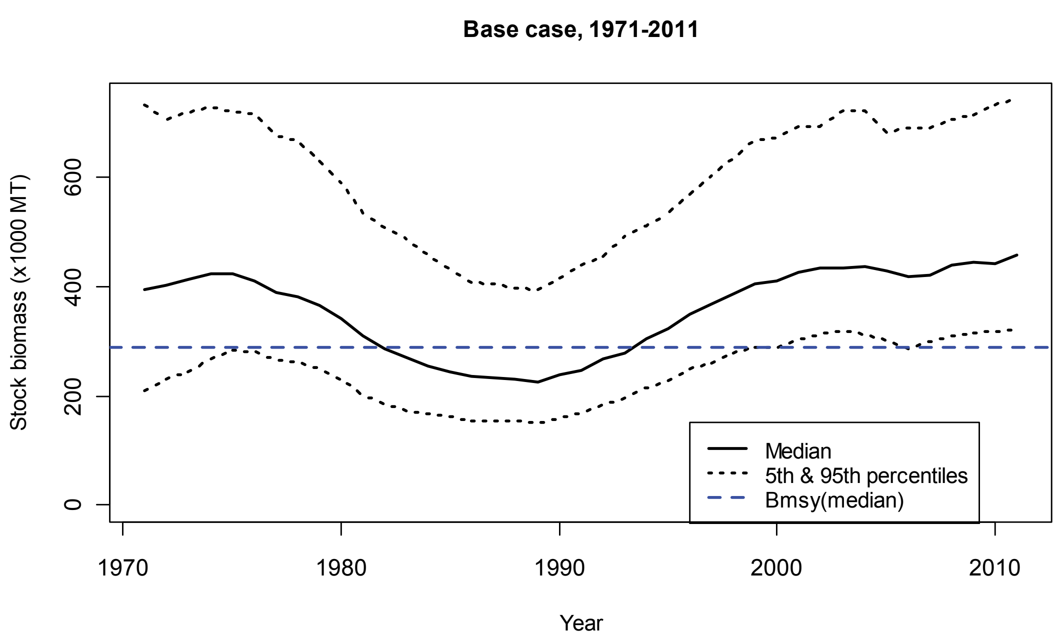


Figure 5E. Kobe plot showing median biomass and fishing mortality trajectories for the base case model of the blue shark (*Prionace glauca*) assessment. Solid blue circle indicates the median estimate in 1971 (initial year of model). Solid gray circle and its horizontal and vertical bars indicate the median and 90% confidence limits in 2011, respectively. Open black circles and black arrows indicate the historical trajectory of stock status between 1971 and 2011.

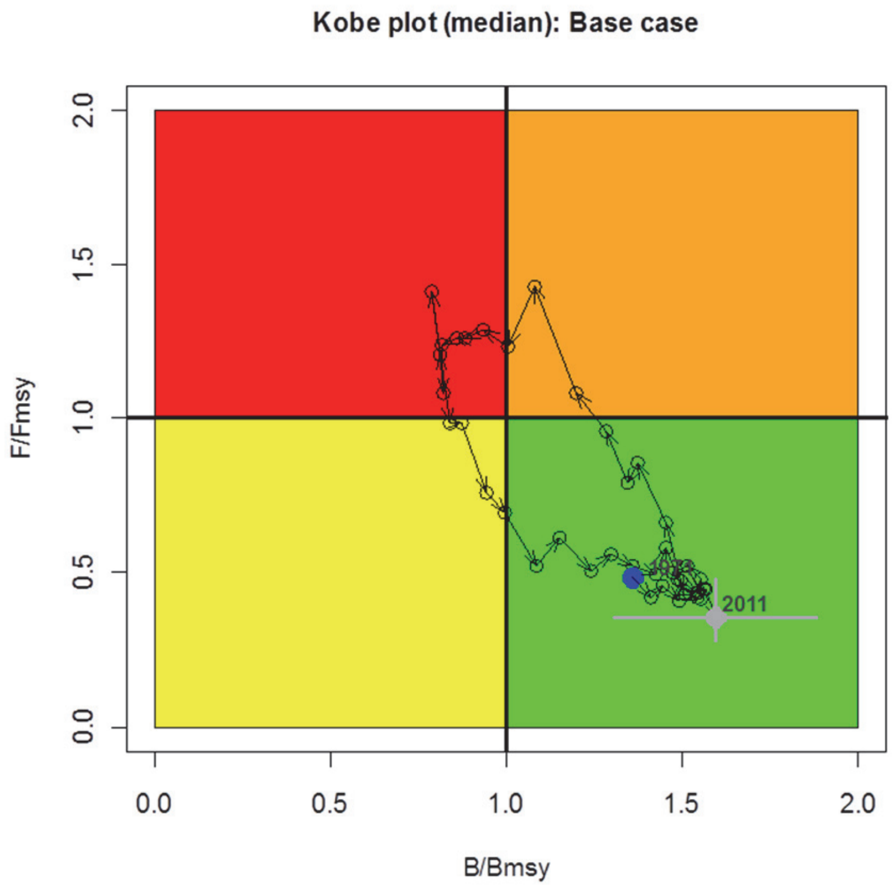


Figure 6E. Comparison of trajectories of median stock biomass between the base case and sensitivity runs. See blue shark (*Prionace glauca*) assessment report text for run identifiers and detailed descriptions of the sensitivity runs.

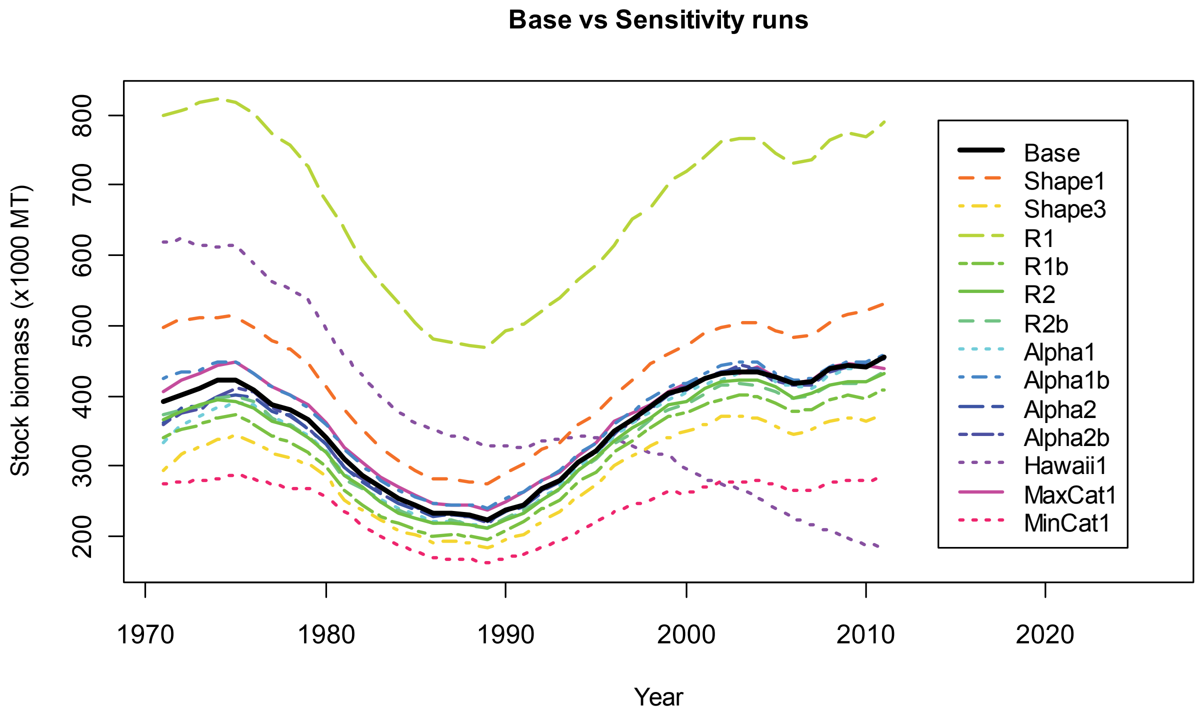
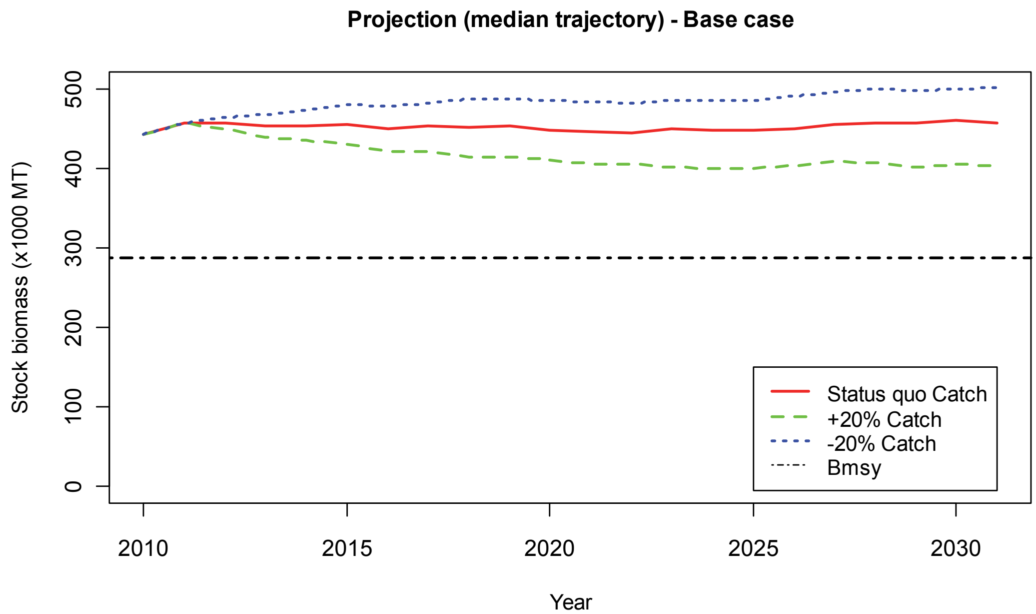
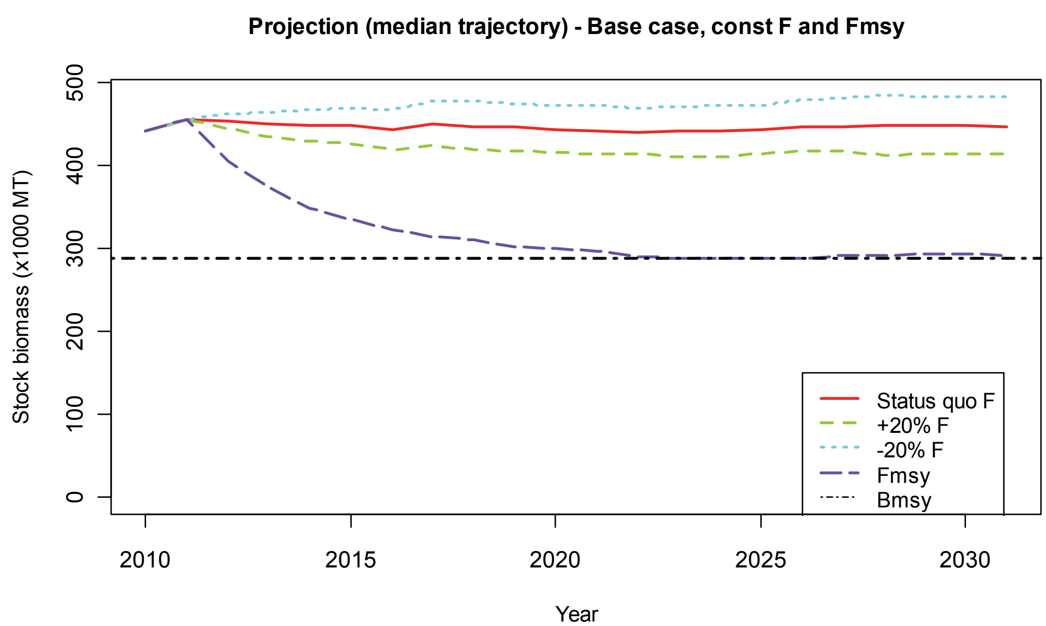


Figure 7E. Comparison of future projected blue shark (*Prionace glauca*) stock biomass (medians) under different constant catch (status quo, +20%, -20%) and constant $F$ harvest policies (status quo, +20%, -20%, and $F_{msy}$) using the base case model. Status quo catch and fishing mortality was based on the average from 2006-2010.



# 1 INTRODUCTION

Blue sharks (*Prionace glauca*) are a common highly-migratory pelagic shark species distributed over temperate and tropical waters worldwide (Nakano and Seki 2003). Their flesh, fins and other body parts are utilized in many countries, and are thus an important fisheries resource. Along with other sharks, blue sharks are considered important in marine ecosystems as they feed at various trophic levels. Like other exploited marine resources, sound scientific knowledge of blue sharks is needed to maintain sustainable fisheries and their role in marine biodiversity.

Concern about the status of shark stocks (Barker and Schluessel 2005) has driven Regional Fishery Management Organizations (RFMOs) to heighten efforts to collect data on sharks from sources of fishery mortality for stock assessments. Unlike commercial targeting of higher value pelagic species such as tunas and billfish, which tend to have high reproductive potential, a greater portion of shark fishing mortality is the result of bycatch, and the reproductive potential of elasmobranchs in general is much lower than teleosts and higher fecundity species (Au et al. 2008). As largely non-targeted species, records of shark catches are often of lower quality and quantity than targeted species. However, the emergence of markets for shark fins has driven demand (Clarke 2004), providing a substantial source of cryptic shark mortality. Without reliable recorded data, it is difficult to estimate the number of mortalities and the population characteristics of those mortalities (size, sex, etc.) from only harvested parts. RFMOs have directed increased efforts to monitor and estimate shark catches and coordinate research into shark biology in an effort to quantify populations with respect to biological reference points (IATTC 2005, Clarke and Harley 2010)

This document presents outcomes of the latest stock assessment for blue sharks in the North Pacific conducted by the ISC Shark Working Group (SHARKWG). In this report, background information (biology and fisheries) of north Pacific blue shark is also summarized along with the assessment results.

# 2 BACKGROUND

## 2.1 Biology

Blue sharks are a temperate to tropical species found worldwide (Nakano and Stevens 2009). Their relative abundance is highest in temperate pelagic zones and decreases in neritic and warmer tropical waters, as well as cooler waters at latitudes higher than approximately 50 degrees. Telemetry studies in the eastern North Pacific indicate they spend most of their time in the mixed layer, with forays as deep as 400 m while occupying temperatures from 14-27 °C predominantly (Weng et al. 2005). Satellite tagging in the southwest Pacific shows a similar preference for surface waters but with dives in excess of 980 m, while occupying comparable water temperatures to those in the eastern North Pacific (Stevens et al. 2010). Within the North Pacific, adult males and females co-occur from the equator to approximately 45 °N, with mating thought to occur in pelagic waters between 20-30 °N. Parturition is thought to occur from 35-45 °N, with female nursery and sub-adult waters from 35-50 °N, while male maturation and sub-adult habitat is believed to be more southerly, between 35-45 °N (Nakano 1994).

#### **2.1.1** Stock structure

Blue sharks have a pan-Pacific distribution, and genetic evidence of distinct population structure within the Pacific is not supported by mitochondrial and microsatellite markers (Taguchi and Yokawa 2013). Conventional tagging in the eastern, central and western North Pacific regions has resulted in recoveries within each North Pacific region, providing evidence of wide movement throughout the North Pacific (Sippel et al. 2011). No tagging data have yet demonstrated movement across the equator (Weng et al. 2005, Stevens et al. 2010, Sippel et al. 2011). Consensus within the ISC Shark Working Group supports a single stock in the North Pacific, distinct from the South Pacific, although more information is needed to further explore the potential for size and sex segregation in the North Pacific as proposed by Nakano (1994).

#### **2.1.2** Reproduction

As indicated above, mating is thought to occur in middle latitudes. Mating scars, fertilized eggs and presence of embryos suggest mating occurs March – August, with litter size ranging from 2-52 (mean 25.2) pups in pregnant females sampled in the western North Pacific (Joung et al. 2011). Litter size has been recorded as high as 135 pups in the Indian Ocean (Gubanov 1975), suggesting reproductive potential could be greater than observed in the western North Pacific. Joung et al. (2011) also estimated a two year cycle of female reproduction although other studies suggest an annual cycle (Nakano 1994). Gestation is estimated to be 9-12 months (Cailliet and Bedford 1983).

#### **2.1.3** Growth

Pups are born at an estimated 40-50 cm fork length (FL) (Joung et al. 2011), and adults reach a maximum length of 380 cm total length (TL). Fifty percent of females are considered mature within the size range of 175-190 cm FL and males at 170-185 cm FL (Nakano et al. 1985, Joung et al. 2011), and age at 50% maturity for females and males are thought to be 5-7 years old and 4-6 years old, respectively (Cailliet and Bedford 1983, Nakano 1994). Improving growth models for blue shark is an ongoing focus of research. A number of growth models have been estimated across a range of geographic locales, with varying sample sizes and methodological approaches to ageing (Cailliet and Bedford 1983, Tanaka 1984, Nakano 1994, Skomal and Natanson 2003, Blanco-Parra et al. 2008, Hsu et al. 2011). For the last north Pacific blue shark assessment, Kleiber et al. (2009) estimated a growth model within the MULTIFAN-CL model.

### **2.2** Fisheries

Like other pelagic sharks, blue sharks are caught in many of the same fisheries as tunas and billfish, including longline, gillnet, troll, purse seine, and hook and line. However, they are targeted much less commonly than tunas and billfish and thus comprise an important component of bycatch from many commercial pelagic fishing operations (Worm et al. 2013). Many are discarded at sea, and the survivorship of those released depends on the condition of the released animals and environmental conditions. Many factors affect condition at release including capture methods, capture duration before fishing gear is retrieved, animal size, and handling at the boat (Musyl et al. 2011). Some information is available about these factors, but overall there are not enough data to understand the many variables affecting blue shark bycatch fishing mortality. Markets have developed for blue shark products in several western Pacific nations and Mexico (e.g. Sosa-Nishizaki et al. 2002). However, some markets value the fins primarily, and cryptic mortality of animals finned and discarded at-sea is a substantial source of uncertainty in blue shark fishing mortality (Clarke 2004).

Currently, the primary source of known blue shark fishing mortality is longline fishing. In the subtropics, deep-set longlines targeting tunas, as well as shallow-sets for swordfish and marlin commonly encounter blue sharks. In more temperate waters, shallow-set longlines targeting swordfish, bluefin and albacore also frequently catch blue sharks. Historically, the primary fleets with effort in these fisheries have been from Japan and Chinese Taipei (Kleiber et al. 2009), and to a lesser extent Korea. More recently, Chinese operations have been identified as another important source of longline fishing effort. Since the late 1980s, Mexico has been developing its pelagic commercial fishing operations, primarily targeting tunas and billfish, but markets developed for shark products have also increased shark targeting (Sosa-Nishizaki et al. 2002). They were also commonly caught in high seas drift gillnet fisheries, operated primarily by Japan, Korea and Chinese Taipei, until the early 1990s before the ban on high seas drift gillnets longer than 2.5 km was enacted in 1992. Drift gillnet fleets now operating within the EEZs of several nations including Japan, Chinese Taipei, Mexico, and the USA currently capture some blue sharks.

### **2.3** Previous assessment

The last stock assessment of north Pacific blue shark was conducted using a fishery time-series ranging from 1971-2002 in Western Pacific (WPO) and Central Pacific (CPO), but excluding the Eastern Pacific (EPO) (Kleiber et al. 2009). Two assessment models were used: a Bayesian Surplus Production (BSP) model (a state-space model implementation was not used in 2009 assessment) and the integrated spatially disaggregated age-structured model, MULTIFAN-CL (Fournier et al. 1998). It included data from the commercial longline and drift gillnet fisheries of Japan, Chinese Taipei, Republic of Korea, and the USA, with additional data provided by the Secretariat of the Pacific Community (SPC). A standardized catch-per-unit-effort (CPUE) index developed using Japanese longline fishery logbooks was used as an abundance index. Japanese catch and CPUE time-series were developed after using a filter to exclude logbook records that were considered unreliable (Nakano and Clarke 2006). The assessment was carried out on numbers of sharks, as opposed to biomass. A limited amount of size data, collected from Japanese and Hawaiian longline fisheries and some gillnet operations was also included in the MULTIFAN-CL model.

The BSP model results indicated that blue sharks in the North Pacific were being harvested below *MSY* (3.58 million sharks $y^{-1}$), and population levels at the end of the model time period (2002) were close to levels at the beginning of the time period (1971). The intrinsic rate of increase (*r*) was assumed to be 0.30, with a median estimate of carrying capacity (*K*) of 49.15 million sharks indicating that *MSY* was 7.4% of *K*. The BSP model fit to the data was considered acceptable, with the caveat that the number of sensitivity runs using alternative assumptions in catch levels and model parameters was limited. Results of the integrated analysis were generally consistent with the BSP model, indicating a decline in the 1980s followed by a population increase in the 1990s with a leveling from 2000-2002.

## **3** DATA

The SHARKWG agreed to use a Bayesian Surplus Production model for the base case assessment, and data were prepared for use within that model structure.

### **3.1** Spatial and temporal stratification

The base case (also sometimes called the 'reference' case) and related sensitivity analyses of this assessment are based on a single North Pacific stock, bounded by the equator in the south, Asia in the west, and North and Central America in the east (Figure 1).

### **3.2** Temporal stratification

An annual (Jan 1-Dec 31) time-series of fishery data for 1971-2011 was used for the assessment.

### **3.3** Definition of fisheries

The SHARKWG estimated catches of many fisheries from different nations and member sources in an effort to understand the sources of fishing mortality (Figure 1). However, all catch estimates were aggregated into a single time-series for the base case model and related sensitivity analyses. The primary sources of catch were from longline and drift gillnet fisheries, with smaller catches also from purse seine, trap, troll, and recreational fisheries. As in the previous assessment, highest catches came from Japan and Chinese Taipei, with newly available Mexican fishery data for this assessment providing a relatively smaller, but important source of catch.

### **3.4** Catch data

Fishery data from ISC member nations and observers were compiled, shared, and reviewed through a series of working papers which were presented and discussed at intercessional meetings of the SHARKWG held in the USA and Japan. Catches were extracted from databases of landings, vessel logbooks, and observer records. When reliable catch data were unavailable, catches were estimated using independently derived standardized CPUE information, often applying assumptions on the species compositions of the catches, to transform effort data into catches. It was agreed to conduct the assessment on units of biomass (as opposed to numbers of animals), so catches were compiled in metric tons (mt) if available, or in numbers of sharks which were converted to biomass with knowledge of the size of sharks caught and an agreed upon length-weight conversion equation. In addition to the catch sources included in the Kleiber et al. (2009) assessment, new sources of catch were available for this assessment including from fisheries operating along the west coast of North America (mainland USA, and Canada, Mexico and other catches north of the equator from IATTC member nations) as well as from China. By nation, the top three sources of blue shark catch were Japan (67.6%), Chinese Taipei (23.9%), and Mexico (4.4%). By gear, longline comprised 82.4%, drift gillnet 13.7% and mixed gears 3.9% of the catch (Figure 2).

Because blue shark is primarily a bycatch species, much of the catch is discarded. The SHARKWG decided to include retained catch and the best estimates for discard mortality in base case catch scenarios, as well as alternative 'high' and 'low' catch scenarios assuming 100% and 0% discard mortality, respectively, for model sensitivity analyses (Figure 3). Discard mortality is expected to differ by gear type and where available, information was considered with respect to each fishery and gear, including proportions of live and dead discards from observer records and telemetry studies.

**3.4.1** Japan

The catches of the offshore (*Kinkai*) and distant-water (*Enyo*) longline fisheries accounted for approximately ¾ of total Japanese catches and were estimated as the product of standardized CPUE and effort during 1976-2010 (Hiraoka et al. 2013). For this estimation, these longline fisheries were categorized by vessel size (offshore or distant-water), operational style (shallow- or deep-sets) and the prefecture of vessel register because the reporting ratios of blue shark were different by these categories. The total numbers of dead removals including discards of Japanese offshore and distant-water fisheries were estimated using the ratio of CPUE between the commercial longliners and the Japanese training vessels. The estimated annual removals were multiplied by the estimated average weight to obtain the annual catch weight. For the estimation of the total removals in 2011, the same methods described above were applied. The CPUE of blue shark was standardized up to 2011 for this purpose but this updated standardized CPUE was not used for this stock assessment because catch and effort data of Japanese longliners in 2011 were heavily affected by the Great East Japan Earthquake. Total removals from 1971-1975 were estimated using the mean ratio of retained catch to estimated total removals during 1976-1980. The mean ratio was calculated for each category of the longline fishery.

Historical catch of blue shark caught by the Japanese coastal fisheries was estimated from Japanese year books since 1951 (Kimoto et al. 2012). These data were reported in species aggregated form as "sharks", and the ratio of the catch of blue sharks to total sharks by fishing gear was calculated using available species-specific landing data. The estimated catches for the coastal longline varied between 200 and 1800 mt, while catches of other longline were between

70 and 750 mt. The estimated catches for the other fisheries were substantially smaller than longline catches, and were below 60 mt.

The catches of blue sharks in high seas squid drift net and high seas large mesh drift net prior to 1993 were obtained from Kleiber et al. (2009). The coastal large mesh drift net fishery within Japan's EEZ started in 1993 (Yokawa et al. 2012). Species-aggregated shark catch were available in Japanese logbooks. Species-specific shark catch data during 2005-2011 was obtained from the wholesale auction records of the Kesennuma fishing port in the Miyagi prefecture, where more than 80% of the coastal driftnet fishery was unloaded. The ratio of blue shark catch to the species-aggregated shark catch was estimated using these auction records to estimate the annual blue shark catch. The ratio of blue shark catch in the period between 1993 and 2004 was assumed to be same as the average during 2005 and 2008 (48%).

#### **3.4.2** Chinese Taipei

Chinese Taipei has small-scale (small boat, near-shore) and large-scale (large boat, distant water) longline fleets. Catch estimates from Taiwanese offshore longline fisheries were the product of logbook effort and CPUE standardized with zero-inflated negative binomial models to account for the high frequency of zero blue shark catch (Tsai and Liu 2013). Smaller vessel longline catches were estimated using observer based species compositions and dockside landing tickets (Chin and Liu 2013).

#### **3.4.3** Mexico

The Instituto Nacional de Pesca (INAPESCA; the Mexican national fisheries and aquaculture institute) provided aggregated shark landings data classified as Tiburon ('large' sharks) and Cazon ('small' sharks) for each Pacific state from 1976-2010. These data were used to estimate blue shark catch (Sosa-Nishizaki 2013) for this assessment. Blue shark is grouped within the Tiburon category and is landed primarily in the Pacific states of Baja California, Baja California Sur, Sinaloa, Nayarit, and Colima. Two fisheries account for most blue shark catch: 1) near-shore artisanal vessels using longlines and/or drift gillnets, which target sharks and swordfish; and 2) offshore medium vessels, which also target sharks and swordfish with similar gears (Sosa-Nishizaki 2013). Regulations have changed through time, leading to different gears and fisheries existing through time. Species composition of blue sharks relative to total shark catches from artisanal fisheries was approximated with the best available information. Catch for 1971-1975 from these fisheries was assumed to be the average catch for these fisheries from 1976-1978, and the 2010 catch was carried forward to 2011. From discussion with Mexican scientists, two additional sources of likely blue shark fishing mortality were also identified. Discards from the medium-sized longline vessel fleet targeting swordfish from 1986-1993 were estimated as a multiple of swordfish landings (Holts and Sosa-Nishizaki 1994) assuming a blue shark to swordfish bycatch ratio of 63:24 (Dreyfus et al. 2008). For a joint venture longline fishery with Japan and Taiwan operating during 1980-1989, effort (Sosa-Nishizaki 1998) was multiplied by blue shark CPUE for a fleet with comparable longline operations (Mendizábal et al. 2000, O. Sosa-Nishizaki pers. comm.).

### 3.4.4 USA

The primary source of US catch was the Hawaii-based longline fleet, which includes deep- and shallow-sets targeting tunas and swordfish, respectively (Walsh and Teo 2012). Estimates of blue shark catch were made from observed sets and logbooks, using catches predicted by a GLM when logbook records were considered unreliable (i.e. unreported catch). Catch for the California pelagic longline fishery, which historically has been small relative to the Hawaii-based fishery and currently is comprised of a single vessel, was estimated by multiplying the CPUE of observed sets by effort recorded in logbooks and average blue shark weight from observer records (Walsh and Teo 2012). A small amount of catch from a short-lived experimental longline fishery that operated in Southern California waters was included (O'Brien and Sunada 1994, Teo 2013). Catches from the US west coast drift gillnet fishery that targets swordfish were estimated from 1981-2010 by Teo et al. 2012. Catches from recreational fisheries were estimated based on 'RecFIN' data collected by telephone surveys and dockside interviews, as well as logbooks from the California Commercial Passenger Fishing Vessel (CPFV) database (Sippel and Kohin 2013).

### 3.4.5 Canada

Canadian catch was negligible and estimated from three fisheries including groundfish longline, groundfish trawl, and salmon fisheries using trolls, gillnets and seines (King 2011).

### 3.4.6 Korea

Korean blue shark catch was assumed to be equal to species-aggregated shark catch reported to the ISC. The Korean annual reports to the two past WCPFC SC meetings indicated that the catch of major shark species includes only blue and porbeagle sharks based on logbooks, and 65% of the catches of major shark species was comprised of blue shark based on observer records for one year. The Korean annual report in 2010 also indicated that the average CPUE of blue shark caught by Korean longliners was 0.07 (number/100 hooks) based on the observer data. Based on this information, it was assumed that all Korean reported catch of species-aggregated sharks are blue sharks, because porbeagle sharks are not distributed in the North Pacific. Using the annual catch and effort data submitted to the ISC, and an average blue shark size of 30 kg, estimated CPUE by year in number of blue sharks per 1000 hooks caught by Korean longliners was ranged from 0.0 to 0.89 which is comparable to the average CPUE obtained by the Korean observer data.

### 3.4.7 China

Species-specific longline catch and effort were available for 2009-2011 and effort data were available back to 2001. The 2009-2011 CPUE was applied to the 2001-2008 effort data to back calculate catch for those years. It was assumed that effort of Chinese longliners in the North Pacific was minimal prior to 2001.

**3.4.8** SPC

SPC provided estimates of blue shark longline catches for non-ISC member countries in the WCPFC area north of the equator using their data holdings. Catch was estimated based on a standardized CPUE value for each 5 x 5 degree cell multiplied by the effort reported in that cell summed on an annual basis. The non-ISC countries represented in the dataset include 12 countries, many of them that likely fish only south of the equator, thus it is believed that the north Pacific blue shark catch of non-ISC member countries represented in the WCPFC database is attributed to Federated States of Micronesia, Kiribati, Marshall Islands, Papua New Guinea and Vanuatu.

**3.4.9** IATTC

IATTC provided catch estimates of blue shark bycatch in tuna purse seines in the north EPO (IATTC 2013). The number of blue sharks caught in number from 1971-2010 was estimated from observer bycatch data, and observer and logbook effort data. Some assumptions regarding the relative bycatch rates of blue sharks were applied based on their temperate distribution and catch composition information. Estimates were calculated separately by set type, year and area. Small purse seine vessels, for which there are no observer data, were assumed to have the same blue shark bycatch rates by set type, year and area, as those of large vessels. Prior to 1993, when shark bycatch data were not available, blue shark bycatch rates assumed to be equal to the average of 1993-1995 rates were applied to the available effort information by set type, area and year. Numbers of sharks were converted to tons by applying an average annual weight estimate derived from blue sharks measured through the IATTC observer program.

**3.5** Abundance indices

Seven candidate standardized CPUE indices were developed from catch and effort data of Japanese, Taiwanese, and US longline fisheries. Increased bias and uncertainty in the assessment results will likely occur if multiple indices with confounding trends are used in the same assessment. A suite of criteria was therefore used by the SHARKWG to select indices for the base case and sensitivity runs from the candidate indices (Table 1). Key criteria included data quality, spatio-temporal coverage of data, potential changes in catchability due to changes in regulations and/or fishing operations, and the adequacy of diagnostics from model-based standardizations.

Based on these criteria, the Japanese “early” (1976-1993) and Japanese “late” (1994-2010) longline indices were selected for the base case model (Figure 4). The Hawaii deep-set (1995-2011) longline index was selected for a sensitivity analysis because it had a declining trend for the period, representing an alternative outlook, and had good quality observer data. However, the spatio-temporal coverage for the index was relatively small, and the fishery has experienced regulatory changes during the time period that may have affected catchability, thus it was considered unlikely to be representative of the entire stock (Figure 4, Table 1).

The estimated coefficient of variation (CV) from the standardization procedures of the three indices used in this assessment were substantially smaller than 0.2. However, the estimated CVs likely did not adequately reflect the process errors in the observed abundance trends. Therefore, all CVs of the indices were initially set to 0.2 and then re-weighted based on preliminary model runs (Section 4.2.4).

### **3.5.1** Base case abundance indices

The Japanese early abundance index was developed from catch-and-effort data from the Japanese *Kinkai* (offshore) shallow-set longline fishery based in Hokkiado and Tohoku prefectures from 1976-1993 (Index 1-1-1a in Hiraoka et al. 2013). The Japanese late abundance index was developed from catch-and-effort data from the Japanese *Kinkai* (offshore) and *Enyo* (distant water) shallow-set longline fisheries based in Hokkiado and Tohoku prefectures from 1994-2010 (Index 2-1-1a in Hiraoka et al. 2013). Detailed descriptions of these fisheries and the development of these indices can be found in several SHARKWG papers (Hiraoka et al. 2011; Hiraoka et al. 2012a, 2012b, 2012c, 2012d; Hiraoka et al. 2013). The primary reason for using these indices in the base case model is that these fisheries have relatively large spatial and temporal coverage as compared to the other candidate indices (Table 1).

Logbook records were used to develop these indices but these logbooks only recorded species-aggregated catch of sharks before 1994. The proportions of blue sharks in the species-aggregated shark catch from 1975-1993 were therefore estimated using a binomial GLM based on species-specific data from 1994-2010. Since it was thought that some vessels do not record blue shark catch, the data for both periods were filtered with the composite reporting rate (RRZ) filter developed by Clarke et al. (2011), which retained data with an individual vessel base reporting rate of >94.6%.

Negative binomial GLMs were used to standardize the abundance indices with explanatory variables including year, area, season, vessel type, and target (Hiraoka et al. 2013). Model diagnostics and residuals did not indicate any substantial bias in the estimated abundance trends. A targeting variable was included in the standardization because Hiraoka et al. (2012b) and Clarke et al. (2011) observed annual changes in the target species of these fisheries, from swordfish and tunas to blue shark. The swordfish catch ratios were divided into 10 categories at each 10$^{th}$ percentile, and used as the target factor.

The Japanese early index indicated a decline in the blue shark abundance from 1976-1989 but the abundance trends appeared to have started to increase during 1990-1993 (Figure 5). The

Japanese late index indicated that the increase in blue shark abundance generally continued during 1994-2010 (Figure 5).

### 3.5.2 Sensitivity run index

The Hawaii deep-set (1995-2011) longline index was developed from the catch-and-effort data gathered by onboard observers on longline vessels based in Hawaii (Walsh and Teo 2012). The deep-set fishery was separated from the shallow-set fishery based on the recorded number of hooks per float (≥15 hooks per float: deep-set; <15 hooks per float: shallow-set). A delta-lognormal GLM was used to standardize the abundance index with explanatory variables including year, season, area, sea surface temperature, time of set, hooks per float, and soak duration (Walsh and Teo 2012). Model diagnostics for this index were good, with relatively normal residuals. In contrast to the Japanese late index during the same period, the Hawaii deep-set index indicated a decline in the blue shark abundance during 1995-2011 (Figure 5).

Although the spatial and temporal coverage of the Hawaii longline index was relatively low, this index was selected for a sensitivity run because the index shows a declining trend in abundance since 1995, which is very different from the base case indices (Table 1) and the SHARKWG wanted to capture the potential range of uncertainty.

### 3.5.3 Other candidate indices

Four other candidate indices were evaluated but not used in this assessment: 1) Hawaii shallow-set longline (Walsh and Teo 2012); 2) Taiwan large-scale longline (Tsai and Liu 2013); 3) Taiwan small-scale longline (Chin and Liu 2013); and 4) Japanese longline training vessel (Clarke et al. 2011). These candidate indices were not used for a variety of reasons. The Hawaii shallow-set longline index had a relatively small spatio-temporal coverage and numerous regulations unrelated to blue shark have also probably influenced fishery operations and affected catchability (Table 1). Both indices from Taiwan longline vessels have relatively large spatial coverage but short temporal coverage (Table 1). In addition, more work needs to be done to understand the representativeness of the data. The Japanese training vessel index had relatively small spatial coverage (approximately the same as the Hawaii indices), poor data quality after 2006 and exhibited strong non-normal residual patterns in the standardization model. In addition, Clarke et al. (2011) indicated that fishing operations appeared to avoid high CPUE areas for blue shark (Table 1).

## 3.6 Length-frequency data

Some size and sex composition data of catches were presented and reviewed by the working group. In many cases the data were in aggregated form covering several years, or size sampling was incomplete across fisheries. The BSP2 model is not length- or age-structured, however the SHARKWG is exploring the use of an integrated age-structured model for north Pacific blue sharks.

# 4 MODEL DESCRIPTION

## 4.1 Bayesian Surplus Production Model

The SHARKWG decided to use a non-equilibrium, age-aggregated Bayesian surplus production (BSP) model (Stanley et al. 2012) and chose the BSP2 implementation developed for ICCAT (McAllister and Babcock 2006[2]). It is a state-space version of BSP model that incorporates stochastic process error in the stock dynamics and thereby allows a more thorough accounting of uncertainty in estimates of stock biomass, future projections, and deviations as compared to a deterministic BSP model. A Bayesian approach was adopted to fit the model to data with the Sampling Importance Resampling (SIR) algorithm, permitting the use of informed priors, which can incorporate prior information and expert judgments. BSP2 fits either a Schaefer or Fletcher/Schaefer production model to time-series of catch and indices of abundance (CPUE), with CVs if available. The parameters that can be fit include carrying capacity (*K*), intrinsic rate of increase (*r*), biomass in the first modeled year defined as a proportion of *K* (*alpha.b0*), the shape parameter for the surplus production function for the Fletcher/Schaefer fit (*n*), the average annual catch for years prior to recorded catch data (*cat0*), and catchability for each CPUE series (*q*). Priors can be used for all parameters. The biomass trajectory can be projected under any catch or harvest policy with the fitted model, as well as associated confidence bounds.

The Schafer surplus production model is expressed as (Prager 1994):

$$\frac{dB_t}{dt} = rB_t - \frac{r}{K} B_t^2 - F_t B_t \qquad (1)$$

where $r$ is intrinsic rate of increase, $K$ is carrying capacity, $B_t$ is biomass at time $t$, and $F_t$ is fishing mortality rate at time $t$. In the Schaefer model, the biomass that produces maximum sustainable yield ($B_{msy}$) is one half of $K$.

A generalized version of the model which allows $B_{msy}/K$ to vary includes a shape parameter, $n$, as well as the additional parameter $m$ (maximum sustainable yield) (Fletcher 1978):

$$\frac{dB_t}{dt} = gm \frac{B_t}{K} - gm \left(\frac{B_t}{K}\right)^n - F_t B_t \qquad (2)$$

where;

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[2] The current software manual of the BSP model (McAllister and Babcock 2006) does not fully explain input parameters, model options and outputs for a state-space version of the BSP model, although it is still useful to learn how to run the software. The ISC Shark Working Group held a three-day workshop in Yokohama, Japan in November 2012 during which Dr. Murdoch McAllister demonstrated how to run the state-space BSP model software.

(3) $$g = \frac{n^{n/n-1}}{n-1}$$

and the inflection point is;

(4) $$\varnothing = \frac{B_{msy}}{K} = \left(\frac{1}{n}\right)^{1/n-1}$$

At $n$=2, the inflection point occurs at 0.5$K$ and this model is identical with the Schaefer model (Prager 2002). This model predicts near-infinite rates of surplus production per capita as abundance decreases to low levels when $n \leq 1$ (i.e. $B_{msy}/K \leq 1/e$) (Quinn and Deriso 1999, Prager 2002). The BSP2 software has been adapted to provide a more realistic production model by fitting a synthesis of the Fletcher and Schaefer models that can take on reasonable values of $r$ at all inflection points (called the Fletcher-Schaefer model) (McAllister and Babcock 2006). For $n > 2$ the original Fletcher model as in equation 2 applies. For $n < 2$ and $B_t/B_{msy} > 1$ the Fletcher model also applies. For $n < 2$ and $B_t/B_{msy} \leq 1$ the functional Schaefer model as in equation 1 applies, where h=2$\varnothing K$, and $\varnothing$ is from equation 4.

A state-space version of the BSP model that incorporates lognormal deviates from total annual stock biomass predictions as described in Stanley et al. 2012 was used:

(5) $$B_t = \left(B_{t-1} + rB_{t-1} - \frac{r}{K} B_{t-1}^2 - F_{t-1}B_{t-1}\right) exp\left(\varepsilon_t - \frac{\sigma_p^2}{2}\right)$$

where the prior probability distribution for the process error term is given by $\varepsilon_t \sim Normal(0, \sigma_p^2)$.

**4.2** Biological and demographic assumptions

This stock assessment assumes that the north Pacific blue shark is a single well-mixed stock, which is supported by current biological information (Section 2). Since this assessment uses a BSP model, it is also assumed that age and sex structure, changes in gear selectivities, and stock-recruitment variability do not substantially affect the estimated stock dynamics.

The most important biological parameters in the BSP model were: $K$, $B_{init}/K$ (biomass in the first year of stock assessment as a proportion of $K$), $r$, and $n$. The model was initialized with priors and associated confidence intervals on each parameter, and the posterior distribution was evaluated after model convergence was obtained. The priors for $K$ and $B_{init}/K$ were based on preliminary BSP model runs, such that the priors were relatively uninformative but the 95% CI encompassed biological plausible values (see section 4.3).

Demographic analyses were used to provide priors for: 1) the intrinsic rate of increase, $r$; and 2) the shape parameter, $n$. However, there was a lack of demographic analyses on north Pacific blue shark that adequately incorporated the uncertainty in the stock's biological characteristics. Therefore, similar to the previous assessment (Kleiber et al. 2009), it was assumed that the north Pacific blue shark had similar biological characteristics to the Atlantic blue shark, and a reasonable range for these parameters was derived from Cortés (2002), which used Monte Carlo simulation to account for the uncertainty in biological characteristics.

#### **4.2.1** Intrinsic rate of increase

The intrinsic rate of increase, $r$, was derived from the population growth rate ($\lambda$) estimate from Cortés (2002) (1.401; 95%CI: 1.284-1.534), using $r = \ln(\lambda)$, which resulted in a mean estimate of 0.34 $y^{-1}$ (95%CI: 0.25-0.43) for $r$. However, a less informative standard deviation of 0.3 was assigned to $r$ because preliminary BSP model runs indicated that the data was informative on this parameter, which allowed the $r$ prior to have lognormal distribution with a 95% CI of 0.19 to 0.61 $y^{-1}$.

#### **4.2.2** Shape parameter

The shape parameter, $n$, was derived from the population growth rate ($\lambda$) and generation time ($T$) estimates from Cortés (2002), the population growth relationship from Fowler (1988), and the relationship between $B_{msy}/K$ and $n$ (eq. 4).

Fowler (1988) observed a population growth relationship between the $B_{msy}/K$ and demographics of a population:

$$\text{(1)} \qquad \frac{B_{msy}}{K} = 0.633 - 0.187(\ln(rT))$$

Given that Cortés found Atlantic blue shark to have a $r$ and $T$ of 0.34 $y^{-1}$ and 7 y, respectively, the mean $B_{msy}/K$ was found to be 0.47 (95%CI: 0.39-0.56). Using eq. 4, the corresponding $n$ for this $B_{msy}/K$ value was approximately 1.71.

The priors for $n$ should covary with the $r$ priors, given the above relationships. However, in order to use a conjoint $r$ and $n$ prior, a highly informative prior is often necessary because the input data in a BSP model tend not to be informative on $n$ (McAllister et al. 2000). Preliminary model runs indicated that the input BSP data for this assessment was not informative on $n$. Given this and that the $r$ and $n$ priors should not be overly informative, a conjoint $r$ and $n$ prior was not used (McAllister et al. 2000). Instead, the $n$ parameter was fixed for the base case at the mean of the estimated $n$ (1.71), corresponding to $B_{msy}/K$=0.47, and sensitivity analyses were performed for a plausible range of values for both $r$ and $B_{msy}/K$ (see sensitivity analyses section 4.4). Since there is unaccounted uncertainty in the Fowler (1988) relationship (eq. 6), the sensitivity analyses encompass a wider range of values for $B_{msy}/K$ (0.3 – 0.6) than the 95% confidence intervals.

### 4.2.3 Weighting of model components

Within the model, inverse variance weighting of each yearly CPUE value was used to estimate variance, $\sigma^2_{j,k}$, according to the following equations;

$$\mathrm{Ln}L = -\sum_{j}\sum_{y}\left[\frac{\left(\ln(I_{j,y}) - \ln(\hat{q}_j\hat{B}_y)\right)^2}{2\sigma^2_{j,k}} + \ln(\sigma_{j,y})\right]$$

where,

$$\hat{q}_j = \left(\frac{\Sigma_y\left(\ln(I_{j,k}) - \ln(\hat{B}_y)\right)/(\sigma^2_{j,k})}{\Sigma_y 1/(\sigma^2_{j,k})}\right)$$

This approach was recommended when weighting uniform variance estimates across different index years (M. McAllister pers. comm.).

Because the BSP2 software treats the total CV for the CPUE indices as the square root of ((observation error CV)$^2$ + (process error CV)$^2$), and the observation error CV for indices is quite small, the total CV is dominated by the process error CV of the indices. CVs for indices were repeatedly adjusted (iterative reweighting) with an initial value of 0.20 until the ratio of the input CV to output CV ranged between 1.1-1.5. This assumes that the CV for each index is constant across years, while SD of the process error for the biomass dynamics equation is fixed at 0.05 (M. McAllister, pers. comm.).

### 4.3 Base case specifications and input parameter choices

Data and starting conditions for the base case model were agreed upon after deliberation during the January 2013 SHARKWG meeting (see Table 2). Based on the demographic analyses described in section 4.2.1, it was agreed to start with a prior for *r* of 0.34 with a standard deviation of 0.3 as in Kleiber et al. (2009).

The prior for *K* (0.8) and its SD (0.5) was uninformative with bounds that were based on preliminary BSP model runs such that plausible values of *K* were well within the bounds. Preliminary BSP model runs also indicated that the $B_{ini}$/K parameter was approximately 0.8. The mean of the $B_{init}/K$ lognormal prior was set to 0.8, with an SD of 0.5 so that the 95% CI of the prior ranged from approximately 0.3 to 2.1.

### 4.4 Model without indices

Relative influence of priors and data on the model's posterior parameter and biomass estimates was examined by running the base case model without fitting to the abundance indices. All but the first year of each abundance index (early and late) was removed, and the CV for those observations changed to 10 from the values estimated from iterative reweighting in the base case. The CVs for the importance function in the SIR algorithm on $K$ and $B_{init}/K$ were set to 1.4 and 0.55, respectively.

**4.5** Specifications and parameter settings for sensitivity runs

Twenty one sensitivity analyses based on alternative model input parameters, abundance indices, and catch scenarios were agreed upon by the working group (see Table 3). Parameter sensitivities focused on intrinsic rate of increase and the shape parameter of the production curve. Scenarios of 'low' and 'high' $r$ were 0.14 and 0.43 respectively, based on ranges considered plausible from demographic analyses (Cortés 2002, Babcock and Cortés 2009). Low (more optimistic) and high (less optimistic) values of the shape parameter considered were 0.3 and 0.6 respectively (see section 4.2.2). The Hawaii deep-set longline abundance index (1995-2011) was used as an alternative to the Japanese 'late' period index (1994-2010), which was used in the base case.

**4.6** Evaluation of model convergence

Model convergence was evaluated with BSP2 model software diagnostics (McAllister and Babcock 2006). In general, the joint posterior distribution is sufficiently well estimated when the maximum weight of any draw is less than approximately 0.5~1% (McAllister and Babcock 2006, M. McAllister pers. comm.), which is a measure of the relative influence of the highest weighted draw. Adequate precision is likely to be achieved after saving at least 20,000 samples, as samples are discarded if parameters exceed their specified bounds. The CV of weights should be relatively low, especially the CV of importance sample weights should be less than the CV of likelihood priors multiplied by priors for the same draw (McAllister et al. 2002).

**4.7** Retrospective analysis

Potential biases in parameter and biomass estimates were investigated using retrospective analysis. Using the base case configuration, the model was terminated during each of the five years prior (2006-2010) to the base case terminal year (2011).

**4.8** Evaluation with Bayes factor

To compare the credibility of each model given the data, Bayes factors (Kass and Raftery 1995) were calculated for the base case and for each of the sensitivity runs. Bayes factors account for both the relative goodness of fit of the model to the data and the parsimony for each of the alternative models. Factor values are calculated as the ratio of the marginal probability of the data for one model to that of another model. The average value for the importance weights from a given model result was used as an approximation of the probability of the data given the model (Kass and Raftery 1995, Stanley et al. 2012). This is known to be a numerically stable approximation for the probability of the data, given the model and approximations obtained through importance sampling. In comparison, Bayes factors for sensitivity runs were compared to the base case. In general, Bayes factors need to depart substantially from 1.0 for inferences to be made from the analysis. However, even fairly large or small departures in the factors can be caused by random chance in the data and/or misspecification of probability models. Thus, intermediate values for Bayes factor (e.g., between 0.001 and 100) should be interpreted with caution. For instance, models which have Bayes factors of between about 0.1 and 0.01 could be interpreted as unlikely but not discredited. If the factor for a model is less than 0.001, then the model could be considered highly unlikely compared to the other (Stanley et al. 2012).

### **4.9** Future projections

Simulations were used to project blue shark stock biomass into the future under three different constant catch scenarios using base case, minimum and maximum catch sensitivity model settings. Projections under three levels of constant $F$ and $F_{msy}$ scenarios were also conducted for the same model settings. Time horizons of the projections were set at 5, 10, and 20 years from the terminal year (2011) of the base case, assuming constant catch of 40,640, 48,770, and 32,510 mt, or assuming constant $F$ of 0.940, 0.1128, and 0.0752 (these $F$ values were calculated using estimates from the base case results). For both constant catch and $F$ harvest policies, three levels of the policies correspond to the average of 2006-2010 catch or $F$ (status quo), 20% increase and 20% decrease from the average, respectively. Catch and $F$ in 2011 were excluded from the averaging because the Japanese longline fleet was greatly affected by the Great East Japan Earthquake of March 2011 (major longline ports in the Tohoku area were destroyed), thus effort and catch subsequently decreased in 2011. For $F_{msy}$ harvest policy, estimated values of $F_{msy}$ in each simulation were used.

## **5** RESULTS

### **5.1** Base case

#### **5.1.1** Base case model convergence

Available diagnostic statistics for model convergence from the BSP2 model software were checked to verify low posterior correlations ($r$ and $K$), an adequate number of saved draws in importance sampling, a low maximum weight of any draw, and that the CV of the weights of the importance draws was less than the CV of the likelihood times priors for the same draws (Table A1). Although the CV of the weights was large, other statistics indicated that the joint posterior distribution was sufficiently estimated and it did not result in non-identifiability of parameters.

#### **5.1.2** Base case model fits

Model fits to the standardized CPUE indices for the base case and the relevant residual plots are shown in Figure 6. Although there were slight systematic trends (positive to negative or vice versa) in residuals for both indices indicating some autocorrelation in the deviates, the residual values themselves were quite small. Thus, overall model fits to the data were considered sufficient.

### 5.1.3 Base case results

Base case stock assessment statistics are shown in Table 4. The marginal posterior distributions for key assessment statistics are plotted in Figure 7. Both posterior mean and median for the maximum *r* were estimated as about 0.40. Although these estimates were slightly larger than the input *r* prior mean of 0.34, this difference between the prior and posterior mean (and variance) indicates that there was some new information contained in the data that updated the distribution of *r*.

The posterior mean and median estimates for the current (2011) stock biomass were 480,000 mt and 456,000 mt (CV=27%), respectively. Both posterior mean and median estimates for the maximum sustainable yield (*MSY*) were 58,000 mt (CV=7%). The median ratio of the 2011 biomass to that at *MSY* ($B_{2011}/B_{msy}$) was approximately 1.6 (CV=12%). The 90% confidence limits (5% and 95% percentiles) of the median for $B_{2011}/B_{msy}$ ranged between 1.3 and 1.9. The posterior median of the 2011 abundance relative to its unfished stock size ($B_{2011}/K$) was 0.80 (CV=12%). The posterior median for the ratio of fishing mortality rate in 2011 to that at *MSY* ($F_{2011}/F_{msy}$) was 0.35 (CV=17%) and the 90% confidence limits of the median was 0.28 to 0.48. The posterior median for the replacement yield (*REPY*) in 2011 was estimated as 43,000 mt (CV=18%). The posterior median ratio of the total catch in 2011 relative to the replacement yield (*Catch*/*REPY*) was 75% (CV=26%). This ratio and $F_{2011}/F_{msy}$ are considered underestimated compared to 'normal' years due to the effects of the Great East Japan Earthquake on the longline fleet in 2011.

Although the marginal posterior distributions indicate moderate to high precision in the estimates for most key parameters, distributions for some estimates were skewed and had long tails (Figure 7). For instance, much of the probability for carrying capacity, *K*, lies above 500,000 mt whereas a large portion of the probability for the ratio of 2011 fishing mortality to that at *MSY*, $F_{2011}/F_{msy}$, is around 0.4.

The median estimate and 90% confidence limits for the historical stock dynamics are plotted in Figure 8. The results of the base case indicated that the stock biomass level of north Pacific blue shark declined from 400,000 mt to about 200,000 mt (below the $B_{msy}$ level) between the mid 1970s and the beginning of 1990s. The stock biomass subsequently increased during the early 1990s and by the early 2000s had recovered to a stock level above $B_{msy}$, and similar to that of the mid 1970s. The blue shark biomass has been stable since, indicating that total catches in recent years have been near replacement yield.

Results from fitting to the data using only priors and a single year of each CPUE index indicate that the abundance indices are quite informative to the results, and the model is not overly influenced by priors. Ranges of posterior distributions estimated from the priors only model are still quite wide. This implies that the priors provide only vague information about most key parameters, and base case and sensitivity results were driven primarily by the data (Figure 9). In the priors only model, the median of $K$ was higher with much wider CI, $r$ was slightly lower with similar CI, $MSY$ was higher with much wider CI, replacement yield was bimodal with wide CI, $F_{2011}/F_{msy}$ density was highest at zero, $B_{2011}/B_{msy}$ density was highest around 2, and stock biomass was essentially flat, ranging between 1200-1500 mt.

Retrospective analysis showed consistency of biomass and parameter estimates when the model was terminated in each year from 2006-2010 (Figure 10). This indicates model consistency and that the final year of the model was not overly influential on fitting to the data and estimating biomass trajectories.

Degrees of stock depletion and overfishing for the base case are illustrated using the "Kobe plot" (Figure 11). The stock biomass of north Pacific blue shark was well above the biomass at the maximum sustainable yield ($B_{msy}$), and the fishing rate well below that at $F_{msy}$ in 1971. The historical trajectory of stock status revealed that north Pacific blue shark had experienced some levels of depletion and overfishing in previous years showing that the trajectory moved through the orange (overfishing), red (overfished and overfishing) and yellow (overfished) zones in sequence in the Kobe plot. In recent years including 2011, the stock condition returned into the green zone and stock biomass has remained above $B_{msy}$ with fishing mortality below $F_{msy}$.

### **5.2** Sensitivity analyses

#### **5.2.1** Sensitivity run model convergence

Similar to the base case, available diagnostic statistics for model convergence from the BSP2 model software were checked to verify low posterior correlations ($r$ and $K$) for all sensitivity run results, an adequate number of saved draws in importance sampling, a low maximum weight of any draw, and that the CV of the weights of the importance draws was less than the CV of the likelihood times priors for the same draws (Table A1).

#### **5.2.2** Sensitivity run model fits

Model fits to the standardized CPUE indices and the residuals for all sensitivity runs were examined in the same way as the base case. Although there were differences in residual patterns between the base case and sensitivity run results, the overall patterns for sensitivity runs were similar (figures not shown) to that for the base case (Figure 12). One exception was the sensitivity run applying the alternative CPUE index (Hawaii deep-set longline index). Model fits for the sensitivity run with the Hawaii longline index were poorer than the base case and other sensitivity runs (Figure 12).

#### **5.2.3** Sensitivity run results

Although there were differences in parameter estimates found between the base case and some sensitivity runs, the sensitivity analyses did not reveal any substantially different stock status compared to the base case, except for the sensitivity run using the Hawaii longline index, run

Hawaii1 (Table 6, Figure 13 and Figure 14). All of the sensitivity runs, except for Hawaii1, indicated that the current (2011) stock biomass of north Pacific blue shark is above $B_{msy}$ (estimates of $B_{2011}/B_{msy}$) and 2011 fishing mortality rate is below $F_{msy}$ (estimates of $F_{2011}/F_{msy}$). Current (2011) catch levels are equal to or less than estimates of replacement yield (estimates of $C_{2011}/REPY$). As mentioned before, the exploitation rate in 2011 was probably underestimated because the Japanese longline effort was affected by the 2011 Great East Japan Earthquake.

*Surplus production function, $B_{msy}/K$ (Shape parameter n)*

Results were relatively sensitive to the choice of $B_{msy}/K$ (runs Shape1 and Shape3 in Table 5, Figure 13 and also see Table 6). Posterior median values for $B_{2011}/B_{msy}$ increased from 1.43 to 1.96 when $B_{msy}/K$ was decreased from 0.6 to 0.3. This difference in $B_{2011}/B_{msy}$ represented the largest range observed among sensitivity runs in which only one input assumption was changed. Median estimates of the ratio of the 2011 fishing mortality to that at *MSY* ($F_{2011}/F_{msy}$) were slightly sensitive to changes in $B_{msy}/K$. However, medians of the ratio of catch in 2011 to replacement yield ($C_{2011}/REPY$) were insensitive to the choice of $B_{msy}/K$.

*r prior mean*

Results were modestly sensitive to the case where the $r$ prior mean was set at a biologically plausible minimum value of 0.14 (R1 in Table 5, Figure 13 and Figure 14, see also Table 7). Posterior medians for $B_{2011}/B_{msy}$ reduced from 1.59 in the base case to 1.43 in R1 sensitivity run. Median values for $F_{2011}/F_{msy}$ increased from 0.36 in the base case to 0.42 in R1 run. In addition, the estimates of current stock biomass ($B_{2011}$) and biomass at *MSY* ($B_{msy}$) were scaled up and down when $r$ prior mean was set to biological minimum and maximum values, respectively. Posterior medians for $C_{2011}/REPY$ were insensitive to changes in $r$ prior mean.

The posterior medians for $r$ were estimated lower (0.18-0.19) than the base case (0.40) when the $r$ prior mean was set at biological minimum value of 0.14 (R1, AlphaR1, AlphaR1c, ShapeR1 and ShapeR1e in Table 5, see also Table 7). However, for several reasons this does not indicate that data contain information that supports lower $r$ values. One reason is that setting an $r$ prior standard deviation at 0.3 makes it hard to estimate a posterior mean larger than 0.2. In addition, sensitivities with a more diffuse $r$ prior resulted in larger posterior medians for $r$, suggesting that the data supported larger $r$ values (R2 and R2b in Table 5). Finally, a Bayes factor comparison indicated that the model run using the biological minimum $r$ prior gave worse fits to the data than the base case (Table 8, see below).

*Maximum and minimum catch scenarios*

Posterior median estimates for $F_{2011}/F_{msy}$ and $C_{2011}/REPY$ varied with maximum and minimum catch scenarios, as expected (MaxCat1 and MinCat1 in Table 5, Figure 13 and Figure 14). Under both scenarios, the median values for $F_{2011}/F_{msy}$ and $C_{2011}/REPY$ were higher than the base case. These higher values resulted from higher current catch under the maximum catch scenario and from lower estimates of the 2011 stock biomass, which gave a smaller replacement yield relative to the 2011 catch under the minimum catch scenario. Estimates for parameters other than these two under the maximum catch scenario were similar to the base case estimates because catch time series were similar between the base case and the maximum catch run (Figure 3).

*Hawaii deep-set longline CPUE index*

Due to the conflicting trends of the Hawaii deep-set longline CPUE index and the late Japanese longline index (Figure 5), a sensitivity run using the Hawaii index resulted in totally different parameter estimates and stock status from the base case and all other sensitivity runs investigated (Hawaii1 in Table 5, Figure 13 and Figure 14). For example, the median estimates of $B_{2011}/B_{msy}$ and $F_{2011}/F_{msy}$ indicate that the current stock biomass ($B_{2011}$) is below that at *MSY* and the current fishing mortality rate exceeds $F_{msy}$. This sensitivity run points to the stock being overfished and that overfishing is occuring (Figure 14). In addition to the criteria for selecting indices to use (Table 1), an analysis of this sensitivity run suggests that the Hawaii deep-set longline index does not adequately represent the overall stock dynamics of north Pacific blue shark. First, the model fit using the Hawaii index (Figure 12) was poorer than that of the base case (Figure 6) and all other sensitivity runs. Second, when iterative re-weighting (described in Model Description section) was done with the same initial total CV (0.2) for CPUE indices, the sensitivity using the Hawaii index resulted in higher estimated total CVs (0.14 for the Japanese longline early period index and 0.22 for the Hawaii index) than the base case (0.12 for the Japanese longline early index and 0.11 for the Japanese longline late index), suggesting that the Hawaii index is relatively inconsistent with the other data (the early index, catch, priors), given the model structure, as compared to using the Japanese longline late period index. Third, projected future stock biomass collapses within seven years with the Hawaii index (result was not shown), which is unlikely given current information. Fourth, the Hawaii longline index was based on a very small portion of total catch (Figure 2), implying the index may not reflect stock dynamics throughout the whole North Pacific.

*Other sensitivity runs*

Results of parameter estimates and stock status for all other sensitivity runs were quite similar to the base case (R2, R2b, Alpha1, Alpha1b, Alpha2 and Alpha2b in Table 5, Figure 13 and Figure 14). Thus, the results were insensitive to these alternative assumptions.

*Historical stock dynamics for sensitivity runs*

Comparison of median trajectories of historical stock dynamics between the base case and various sensitivity runs showed that overall patterns of the dynamics for the sensitivity runs were fairly similar to that for the base case and the only differences were estimated levels of stock biomass (Figure 13). The highest biomass level was estimated when *r* prior mean was set to a biologically plausible minimum value of 0.14 (R1) while the lowest level resulted from the minimum catch scenario (MinCat1). Here again, the sensitivity run using Hawaii longline CPUE index was the only exception, indicating a continual decline of blue shark biomass throughout all assessment years. Overall, the general consistency of sensitivity analyses supports the historical stock dynamics represented by the base case model.

#### **5.2.4** Bayes factor evaluation

None of the Bayes factors indicated that any of the alternative sensitivity runs could be viewed as much less or more likely than the base case (Table 8). The sensitivity run assuming a biologically plausible minimum for *r* prior mean set at 0.14 had a Bayes factor of 0.13 (R1), which indicated that the base case showed a better fit to the data than with the lower alternative *r* prior, whereas the assumption of a biological maximum for *r* prior mean set at 0.43 resulted in a Bayes factor of 1.33 (R1b), indicating that the base case gave a slightly worse fit than the higher alternative *r* prior. This was also apparent in the base case run where the posterior distribution for *r* was updated to support higher values of *r* than its prior (Figure 7).

The assumption of $B_{init}/K$ prior mean set at 0.5 produced a Bayes factor of 1.13 (Alpha1), showing that this lower alternative provided a slightly better fit to the data than the base case. This was also apparent in the base case run because the posterior mean and median for $B_{init}/K$ in the base case supported lower values of $B_{init}/K$ (0.63 and 0.64, respectively) than its prior mean. All other alternative sensitivity runs had lower Bayes factor values than the base case, indicating that the base case model fit was better than these alternatives.

### **5.3** Future projections

#### **5.3.1** Base case

Figure 15 and Figure 16 illustrate comparisons of median future projections for blue shark biomass under different scenarios using the base case model: status quo constant catch, status quo constant fishing mortality rate (*F*) and $F_{msy}$ (*F* at MSY) harvest policies. Status quo catch and *F* policies were based on the average catch and *F* over the recent 5 years of 2006-2010. Under the status quo policy, the stock biomass of north Pacific blue shark will remain stable. This was expected because the current catch level was estimated at near replacement yield (Table 9). Even under +20% constant catch and constant *F* harvest policies, the blue shark stock will stay above the biomass at maximum sustainable yield, $B_{msy}$, throughout the projection time horizon with a probability higher than 95% (Table 9). Similarly, future fishing mortality will remain well below $F_{msy}$.

Future projected catches (median values) under constant *F* and $F_{msy}$ harvest policies were shown in Figure 17 and Table 9. A status quo constant *F* policy will produce about 38,000 mt to 43,000 mt catch over the projection years.

### **5.3.2** Maximum and minimum catch scenarios

Figure 18 and Figure 19 show comparisons of median future projections for blue shark biomass under constant catch, constant $F$ and $F_{msy}$ harvest policies for the maximum catch scenario. Similar to the base case, under the status quo policies of both constant catch and $F$, the biomass level of the north Pacific blue shark will remain unchanged on a median basis. This was expected because the current catch level was estimated as near replacement yield (Table 9). Even under +20% constant catch and constant $F$ harvest policies, the blue shark stock will remain above the biomass at *MSY* with at least 89% probability and the fishing mortality rate will remain well below $F_{msy}$ (Table 9).

Future catches (median values) under constant $F$ and $F_{msy}$ harvest policies are shown in Figure 20 and Table 9. Catch levels between about 37,000 mt and 44,000 mt is expected under a status quo $F$ policy. Trajectories of median future shark biomass under different constant catch, constant $F$ and $F_{msy}$ harvest policies for the minimum catch scenario were plotted in Figure 21 and Figure 22. Future catches (median values) under constant $F$ and $F_{msy}$ harvest policies are shown in Figure 23 and Table 9. Trajectory patterns for stock dynamics and catch time series were highly similar to the base case and of the maximum catch alternative, with only differences in projected stock biomass and catch levels.

# **6** STOCK STATUS

## **6.1** Status of the stock

Based on the trajectory of the base case model, median stock biomass of blue shark in 2011 ($B_{2011}$) was estimated to be 456,000 mt (Figure 8). Median annual fishing mortality in 2011 ($F_{2011}$) was 7.14% of $B_{2011}$. Catch in 2011 ($C_{2011}$) was estimated to be 75% of replacement yield (*REPY*). Stock status is reported in relation to maximum sustainable yield (*MSY*). Stock biomass in 2011 was approximately 60% higher than $B_{msy}$ and $F_{2011}$ was estimated to be well below $F_{msy}$ (Table 4; Figure 11).

While the results varied depending upon the input assumptions, there was general agreement in nearly all scenarios in terms of the key model results: stock biomass was near a time-series high in 1971, fell to its lowest level in the late 1980s, and subsequently increased gradually and has leveled off at a biomass similar to that at the beginning of the time-series (Figure 13). A single scenario using CPUE data for the Hawaii-based deep longline fleet for 1995-2011 in place of the Japan shallow longline index for 1994-2010, showed a continual decline in stock biomass from 1971 to 2011. However, the Hawaii index was not considered to be representative of the stock due to the relatively small amount of catch and spatial coverage and the potential impact of regulatory changes in the fishery.

Future projections of the base case model show that median BSH biomass in the North Pacific will remain above $B_{msy}$ under the catch harvest policies examined (status quo, +20%, -20%). Similarly, future projections under different $F$ harvest policies (status quo, +20%, -20%) show that median BSH biomass in the North Pacific will remain above $B_{msy}$ (Table 9; Figure 15; Figure 16).

Projections under different catch and fishing mortality policies were also conducted for the maximum and minimum catch model scenarios. In all cases, patterns of trajectories were essentially the same as for the base case, and the projected stock biomass remained above $B_{msy}$. Projected stock biomass was lower for runs with either catch or $F$ 20% above current, as expected, but remained above $B_{msy}$ (Table 9).

In summary, based on the base case and plausible model scenarios, the stock is not overfished and overfishing is not occurring.

### **6.2** Conservation information

The Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC) are responsible for management of pelagic sharks caught in international fisheries for tuna and tuna-like species in the Pacific Ocean.

The BSH biomass level in 2011 in the North Pacific is estimated to be near the highest levels seen in the time-series, and current fishing mortality rates and catch levels are below those expected to produce *MSY*.

Model inputs for this assessment have been improved since the previous assessment and provide the best available scientific information. However, there are uncertainties in the time series for estimated catch and abundance indices for BSH in the North Pacific, as well as for many life history parameters used to estimate stock productivity. Available catch composition information demonstrates evidence of spatial and temporal stratification by size and sex, which suggests that use of other modeling approaches, if sufficient data are available, may provide additional insights into stock dynamics. Improvements in the monitoring of BSH catches, including recording the size and sex of sharks retained and discarded for all fisheries, as well as continued research into the biology and ecology of BSH in the North Pacific are recommended.

### **6.3** Limitations and Research Needs

This was the first shark stock assessment conducted by the SHARKWG of the ISC. As such, there were no historical time series of blue shark catch by ISC members available to the SHARKWG. In many cases, national catch statistics do not contain shark catch or landings data by species, at least for historical catch. Additionally, discarded shark catch has not typically been accounted for in historical landings statistics. The SHARKWG has recreated historical catches, including discards, although more work should be done to improve the input data and reduce uncertainties about fisheries that catch blue sharks in the North Pacific. Furthermore, additional biological and life history studies on blue sharks in the North Pacific are needed to improve the biological parameters used in the population dynamics modeling.

*Unaccounted catch*

Central American nations including Costa Rica and Panama are known to have fisheries which target sharks, as well as ports where foreign vessels land shark catches. The nature of these fisheries and landings arrangements are highly uncertain and it is unknown if, or to what extent, Central American or foreign vessels are fishing for sharks in the North Pacific. The IATTC is working with Central American nations to characterize these fisheries and ports, and identify records associated with them. At the time of the assessment, there was not enough information to estimate north Pacific blue shark catches from these fisheries. Similarly, in the north WPO, catch data were not available for many nations that potentially catch blue sharks during pelagic fishery operations. The SHARKWG should explore other sources of blue shark data for use in future assessments.

*Abundance indices*

Few CPUE indices are available that are derived from fisheries operating over a large portion of the range of the stock and cover a significant period of time. The SHARKWG reviewed seven candidate standardized CPUE indices based on catch and effort data of Japanese, Taiwanese, and US longline fisheries and selected indices based on data quality, spatio-temporal coverage of data, potential changes in catchability due to changes in regulations and/or fishing operations, and the adequacy of diagnostics from model-based standardizations. It was felt that several of the indices had some good qualities. For example, the SHARKWG rejected the CPUE index derived from Japanese Research Training Vessel data (Clarke et al. 2011) for incorporation into the BSP model because it did not meet several of the key criteria applied to selection of the other indices; however, as the data were collected during research operations, they should be relatively reliable. With improvements in standardization methods that result in better statistical diagnostics, as well as better accounting for potential effects of changes in regulatory regimes or targeting practices, some of the indices evaluated prove useful in future assessments. Future research should address diagnostic issues, consider integrating varied data sources that represent overlapping operations, and investigate alternate filtering methods that balance the removal of catch records which are likely to be under-reported, but retain those which have low catch but may be accurate.

*Length-frequency data*

The SHARKWG reviewed size and sex composition data from fisheries with available data. In many cases the data were aggregated, covering several seasons, years or areas or without corresponding sex data. The size sampling was incomplete across fisheries. The SHARKWG selected to focus on providing best estimates of catch and effort, with future investigation to focus on delivering the most appropriate size data. The lack of reliable size data was one rationale for selecting a BSP model for this assessment because it does not require length composition information. However, the available catch composition information demonstrates some evidence of spatial and temporal stratification by size and sex. If sufficient size data can be made available, other modeling approaches might provide additional insights into stock dynamics. In conjunction with future provision and filtering of appropriate size data, the SHARKWG will explore the use of an integrated length-structured model for north Pacific blue shark and it is anticipated that a preliminary model will be available in the near future.

*Pacific-specific estimates of intrinsic rate of increase (r)*

There were discrepancies between several published growth curve estimates for north Pacific blue shark that could not be reconciled by the SHARKWG. Apparent regional differences in length at infinity ($L_{inf}$) and the growth curve coefficient ($K$) may be real or may be artifacts of differences in sample sizes and size ranges between studies. In addition, consistent information on the female reproductive cycle (1 year vs. 2 years) was not available. Reliable growth curve estimates and information on reproductive cycle are required for estimating intrinsic rate of increase ($r$), which is an important parameter required for production type models. In lieu of a single North Pacific or resolved region-specific growth curves, the BSP model employed productivity parameters similar to those estimated for blue shark in the Atlantic (Cortés 2002). The SHARKWG will undertake future research into resolving differences between growth curve estimates in the North Pacific and developing reliable growth curve estimates, particularly in the eastern Pacific region. The SHARKWG recommends that future research focuses on collecting monthly samples of mature females to address this knowledge gap.

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# TABLES

Table 1. Characteristics of candidate abundance indices proposed to represent relative abundance of north Pacific blue shark (*Prionace glauca*) and criteria used to evaluate the indices. Reproduced from April 2013 SHARKWG Report (ISC 2013).

| | **Hawaii Deep-set Longline** | **Hawaii Shallow-set Longline** | **Taiwan Large-scale Longline** | **Taiwan Small-scale Longline** | **Japan Early Offshore Shallow (Hokkaido & Tohoku)** | **Japan Late Offshore & Distant Water (Hokkaido & Tohoku)** | **Japan Research Training Vessel Region 2 Index** |
|---|---|---|---|---|---|---|---|
| **Quality of Observations** | Good because observer data is used with ~5-20% observer coverage and discards are recorded | Good because observer data is used with ~5-100% observer coverage and discards are recorded | Good because observer data is used but recorded discard data may not be representative | Catch data are representative but effort data were estimated | Relatively reliable because 94.6% filtered data applied, logbook data more reliable by filtering | Relatively reliable because 94.6% filtered data applied and logbook were validated by training vessel and observer data | Species ID believed good until 2000, quality declining since, after 2005-2006 discarding may be underreported and data quality considered bad |
| **Spatial distribution** | Relatively small (Areas 4 & 5) | Relatively small (Areas 2 & 5) | Large (Areas 1-5) | Large (Areas 1-5) | Medium (Area 1 & 3) | Large (Area 1, 2, 3 & 4) | ISC area 2, and some area 4 |
| **Size/age distribution** | 90% of catch from females: 175-275 cm TL; males: 175-300 cm TL | 90% of catch from females: 100-275 cm TL; males: 100-300 cm TL | 60 to 340 cm TL | 90 cm to 320 cm TL | no information | 90-170 cm PCL | 120-200 PCL, median 160 |
| **Statistical soundness** | Yes. Delta-lognormal model was used and model diagnostics were good | Yes. Delta-lognormal model was used and model diagnostics were good | Some diagnostics provided | Diagnostics provided | Yes | Yes | No. Strong patterns in residuals and departure from normality in qq plot; not enough information provided (e.g. deviance table, CV's) |
| **Temporal coverage** | 1995-2011 | 1995-2001; 2004-2011 | 2004-2010 | 2001-2003; 2005-2010 | 1976-1993 | 1994-2010 | 1993-2008 |

| | **Hawaii Deep-set Longline** | **Hawaii Shallow-set Longline** | **Taiwan Large-scale Longline** | **Taiwan Small-scale Longline** | **Japan Early Offshore Shallow (Hokkaido & Tohoku)** | **Japan Late Offshore & Distant Water (Hokkaido & Tohoku)** | **Japan Research Training Vessel Region 2 Index** |
|---|---|---|---|---|---|---|---|
| **Catchability Changes (due to management, fishing practices, etc.)** | Finning ban from 2000 (probably limited effect on Q) | Ban in shark finning from 2000 (probably limited effect on Q); Shallow-set longline ban from 2001-2004 (likely affects Q); hooks and bait requirements after 2004; limits on turtle bycatch | Ban in finning from 2005 (probably limited effect on Q) | Ban in finning from 2005 (probably limited effect on Q) | No regulation, gear or targeting change | No regulation, gear or targeting change | Opportunistic fishing effort, so changes in catchability are hard to determine |
| **Relative catch contribution** | ~1500 to 2000 mt annually | ~1500 to 2000 mt annually | <500 tons from 2003 | >10,000 tons from 2004 | 19,000-55,000 mt | 13,000-24,000 mt | ~50mt annually |
| **Decision** | Use in sensitivity run | Not used | Not used | Not used | Used in base-case model | Used in base-case model | Not to use in BSP modeling; not to use for SS3 reference case |
| **Decision reason** | Use in sensitivity run because it has some desirable characteristics and has different trend from others, but area too small to be primary index | Multiple management changes likely affected catchability | Time-series is relatively short and some questions remain about the representativeness of recorded number of discards | Time-series is relatively short, especially since the index in the early period (2001-2003) should not be used due to incomplete sampling of effort | Large spatial and temporal coverage | Large spatial coverage | Too late to evaluate properly; overlapping in area and operation with HI index that shows similar trend; very small proportion of overall catch |

| | Hawaii Deep-set Longline | Hawaii Shallow-set Longline | Taiwan Large-scale Longline | Taiwan Small-scale Longline | Japan Early Offshore Shallow (Hokkaido & Tohoku) | Japan Late Offshore & Distant Water (Hokkaido & Tohoku) | Japan Research Training Vessel Region 2 Index |
|---|---|---|---|---|---|---|---|
| **Remarks** | | | Discard rate is suggested to be higher than recorded by observers because CPUE is unexpectedly low | Negligible discard rate; more confidence in late compared to early time series due to higher coverage of effort sampling in the late period | | | Region 4 CPUE index seems unreasonable, so concern was raised about the methods as applied to region 2; Gulland index seems to indicate the vessels were avoiding the high CPUE areas for blue sharks |

Table 2. Base case specifications and key input parameter choices for the North Pacific Ocean blue shark (*Prionace glauca*) assessment.

| **Specifications/Parameters** | **Value** | **Description/comments** |
|---|---|---|
| $K$ | Uniform distribution on log($K$) | Range: [50, 2000] x 1000 MT |
| $r$ prior mean | 0.34, SD=0.3 | Based on Cortes (2002) and Kleiber et al. 2009 |
| $B_{init}/K$ (*alpha.b0*) prior mean | 0.8, SD=0.5 | Lower mean and more diffuse prior than Kleiber et al. 2009, based on preliminary runs conducted in the Shark WG meeting in January 2013.<br>*init* (initial year of assessment) = 1971 |
| Surplus production function | $B_{msy}/K$=0.47 | Fletcher-Schaefer model, corresponded to shape parameter of $n$=1.71 |
| Catch | | Total dead removals estimated by WG members (for details, see DATA section of this report) |
| Abundance index | Japanese offshore shallow longline CPUE index (of Hokkaido and Tohoku fleets) for 1976-1993<br><br>Japanese offshore and distant water longline CPUE index (of Hokkaido and Tohoku fleets) for 1994-2010 | For details, see CPUE index section of this report |
| CV's for abundance indices | 0.15 for Japanese offshore shallow longline CPUE index for 1976-1993<br><br>0.14 for Japanese offshore and distant water longline CPUE index for 1994-2010 | Considering that total CV for CPUE index is treated as the square root of ((observation error CV)$^2$+(process error CV)$^2$) in the BSP2 software and the observation error CV for index is quite small, the total CV is dominated by the process error CV for index. To set the total CV for CPUE index properly, inputted CV for index was repeatedly adjusted (iterative reweighting) with an initial value of 0.20 until the ratio of inputted CV to outputted CV got roughly equal to 1.1-1.5 assuming that the CV for index is constant across years, while SD of the process error for the biomass dynamics equation is fixed at 0.05 (M. McAllister, pers. comm.). |

Table 3. Specifications and key parameter settings for sensitivity runs in the North Pacific Ocean blue shark (*Prionace glauca*) assessment .

| Category description | Run ID | Run description/comments |
|---|---|---|
| $B_{msy}/K$ (shape parameter n) | Shape1<br>Shape3 | $B_{msy}/K$ = 0.3 (n = 0.68)<br>$B_{msy}/K$ = 0.6 (n = 3.39) |
| $r$ prior mean | R1<br>R1b | mean = 0.14 (from Babcock and Cortes 2009)<br>mean = 0.43 (From Cortes 2002) |
| $r$ prior SD | R2<br>R2b | SD = 0.5<br>SD = 0.7 |
| $B_{init}/K$ (*alpha.b0*) prior mean | Alpha1<br>Alpha1b | mean = 0.5<br>mean = 1.0 |
| $B_{init}/K$ (*alpha.b0*) prior SD | Alpha2<br>Alpha2b | SD = 0.7<br>SD = 0.9 |
| $r$ versus $B_{init}/K$ grids | AlphaR1<br>AlphaR1b<br>AlphaR1c<br>AlphaR1d | $r$ prior mean = 0.14, $B_{init}/K$ prior mean = 0.5<br>$r$ prior mean = 0.43, $B_{init}/K$ prior mean = 0.5<br>$r$ prior mean = 0.14, $B_{init}/K$ prior mean = 1.0<br>$r$ prior mean = 0.43, $B_{init}/K$ prior mean = 1.0<br>These sensitivity runs allow grid comparison to examine interactions of $r$ [0.14, 0.34(Base), 0.43] and $B_{init}/K$ [0.5, 0.8(Base), 1.0] along with Alpha1, Alpha1b, Base, R1 and R1b sensitivity runs above. |
| $r$ versus $B_{msy}/K$ (shape parameter $n$) grids | ShapeR1<br>ShapeR1b<br>ShapeR1e<br>ShapeR1f | $r$ prior mean = 0.14, $B_{msy}/K$ = 0.3 ($n$ = 0.68)<br>$r$ prior mean = 0.43, $B_{msy}/K$ = 0.3 ($n$ = 0.68)<br>$r$ prior mean = 0.14, $B_{msy}/K$ = 0.6 ($n$ = 3.34)<br>$r$ prior mean = 0.43, $B_{msy}/K$ = 0.6 ($n$ = 3.39)<br>These sensitivity runs allow grid comparison to examine interactions of $r$ [0.14, 0.34(Base), 0.43] and $B_{msy}/K$ [0.3, 0.47(Base), 0.6] ($n$[0.68, 1.71, 3.39]) along with Shape1, Shape3, Base, R1 and R1b sensitivity runs above. |
| Alternative CPUE index | Hawaii1 | Hawaii deep-set longline CPUE index for 1995-2011 was used instead of Japanese offshore and distant water longline CPUE index for 1994-2010.<br>For this sensitivity run, CV for Hawaii index was set to 0.25 and CV for Japanese offshore shallow longline CPUE index for 1976-1993 was set to 0.2 by applying the same reweighting method used in Base case. |
| Alternative catch scenario | MaxCat1<br>MinCat1 | Maximum catch<br>Minimum catch<br>Maximum and minimum catches were estimated by WG members (for details, see DATA section of this report) |

Table 4. Base case model results of the North Pacific Ocean blue shark (*Prionace glauca*) assessment - mean, standard deviation, and coefficient of variation, median and 90% confidence intervals of important biological parameters and reference points. REPY and $C_{2011}$ indicates replacement yield and catch in 2011, respectively.

| Variable | Mean | SD | CV | $5^{th}$ Percentile | Median | $95^{th}$ Percentile |
|---|---|---|---|---|---|---|
| $r$ | 0.41 | 0.10 | 0.24 | 0.25 | 0.40 | 0.58 |
| $K$ ('000 t) | 645 | 171 | 0.27 | 432 | 613 | 961 |
| $MSY$ ('000 t) | 58 | 4 | 0.07 | 52 | 58 | 65 |
| $B_{MSY}$ ('000 t) | 303 | 80 | 0.27 | 203 | 288 | 452 |
| $B_{1971}$ ('000 t) | 407 | 80 | 0.42 | 208 | 393 | 732 |
| $B_{2011}$ ('000 t) | 480 | 170 | 0.27 | 323 | 456 | 741 |
| $B_{2011}/B_{MSY}$ | 1.59 | 131 | 0.12 | 1.30 | 1.59 | 1.88 |
| $B_{2011}/B_{1971}$ | 1.25 | 0.18 | 0.30 | 0.81 | 1.17 | 1.94 |
| $B_{2011}/K$ | 0.75 | 0.37 | 0.12 | 0.65 | 0.80 | 0.94 |
| $F_{MSY}$ (%) | 20.2 | 4.9 | 0.24 | 12.6 | 20.0 | 29.0 |
| $F_{2011}$ (%) | 7.2 | 1.7 | 0.23 | 4.4 | 7.1 | 10.0 |
| $F_{2011}/F_{MSY}$ | 0.36 | 0.06 | 0.17 | 0.28 | 0.35 | 0.48 |
| $REPY$ ('000 t) | 42 | 8 | 0.18 | 28 | 43 | 53 |
| $C_{2011}/REPY$ | 0.77 | 0.20 | 0.26 | 0.59 | 0.75 | 1.08 |

Table 5. Medians and 90% credibility intervals drawn from the posterior distributions for seven parameters. Biomass values are in 1000 metric tons. See Table 3 for run identifiers and detailed descriptions of the sensitivity runs.

| Run ID | $r$ | | | $B_{msy}$ | | | $B_{2011}$ | | | Replacemnt yield | | | $B_{2011}/B_{msy}$ | | | $F_{2011}/F_{msy}$ | | | $C_{2011}/Rep\ Y$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5% | Median | 95% | 5% | Median | 95% | 5% | Median | 95% | 5% | Median | 95% | 5% | Median | 95% | 5% | Median | 95% | 5% | Median | 95% |
| **Base** | 0.25 | 0.40 | 0.58 | 203 | 288 | 452 | 323 | 456 | 741 | 28 | 43 | 53 | 1.30 | 1.59 | 1.88 | 0.28 | 0.36 | 0.48 | 0.59 | 0.76 | 1.08 |
| | **$B_{msy}/K$ (shape parameter $n$)** | | | | | | | | | | | | | | | | | | | | |
| **Shape1** | 0.26 | 0.41 | 0.62 | 185 | 272 | 441 | 362 | 529 | 888 | 33 | 44 | 52 | 1.48 | 1.96 | 2.52 | 0.20 | 0.29 | 0.43 | 0.62 | 0.74 | 0.99 |
| **Shape3** | 0.22 | 0.33 | 0.47 | 185 | 262 | 389 | 258 | 375 | 557 | 21 | 41 | 53 | 1.24 | 1.43 | 1.61 | 0.32 | 0.38 | 0.46 | 0.61 | 0.71 | 1.02 |
| | **$r$ prior mean** | | | | | | | | | | | | | | | | | | | | |
| **R1** | 0.12 | 0.19 | 0.30 | 371 | 596 | 884 | 509 | 791 | 1339 | 29 | 46 | 60 | 0.98 | 1.43 | 1.86 | 0.27 | 0.42 | 0.66 | 0.52 | 0.71 | 1.07 |
| **R1b** | 0.29 | 0.45 | 0.65 | 183 | 254 | 388 | 289 | 408 | 622 | 28 | 42 | 51 | 1.35 | 1.61 | 1.91 | 0.28 | 0.35 | 0.45 | 0.59 | 0.77 | 1.07 |
| | **$r$ prior SD** | | | | | | | | | | | | | | | | | | | | |
| **R2** | 0.22 | 0.43 | 0.68 | 178 | 271 | 484 | 289 | 433 | 762 | 29 | 43 | 53 | 1.26 | 1.60 | 1.88 | 0.28 | 0.35 | 0.48 | 0.60 | 0.75 | 1.09 |
| **R2b** | 0.22 | 0.43 | 0.68 | 175 | 270 | 478 | 281 | 435 | 744 | 27 | 42 | 52 | 1.33 | 1.61 | 1.90 | 0.28 | 0.35 | 0.46 | 0.58 | 0.76 | 1.08 |
| | **$B_{init}/K$ (*alpha.b0*) prior mean** | | | | | | | | | | | | | | | | | | | | |
| **Alpha1** | 0.26 | 0.41 | 0.59 | 203 | 285 | 437 | 320 | 451 | 684 | 29 | 43 | 55 | 1.27 | 1.59 | 1.87 | 0.28 | 0.35 | 0.48 | 0.58 | 0.75 | 1.03 |
| **Alpha1b** | 0.25 | 0.39 | 0.58 | 203 | 295 | 452 | 321 | 458 | 717 | 28 | 43 | 52 | 1.30 | 1.57 | 1.89 | 0.28 | 0.36 | 0.48 | 0.60 | 0.75 | 1.09 |
| | **$B_{init}/K$ (*alpha.b0*) prior SD** | | | | | | | | | | | | | | | | | | | | |
| **Alpha2** | 0.25 | 0.41 | 0.59 | 200 | 286 | 450 | 313 | 453 | 719 | 29 | 43 | 54 | 1.26 | 1.59 | 1.88 | 0.28 | 0.36 | 0.49 | 0.55 | 0.74 | 1.02 |
| **Alpha2b** | 0.26 | 0.40 | 0.59 | 200 | 291 | 459 | 318 | 456 | 710 | 29 | 44 | 54 | 1.29 | 1.58 | 1.87 | 0.28 | 0.36 | 0.48 | 0.60 | 0.74 | 1.04 |
| | **$r$ versus $B_{init}/K$ (*alpha.b0*) grids** | | | | | | | | | | | | | | | | | | | | |
| **AlphaR1** | 0.12 | 0.18 | 0.29 | 388 | 620 | 868 | 524 | 780 | 1292 | 32 | 48 | 63 | 0.93 | 1.36 | 1.78 | 0.29 | 0.45 | 0.66 | 0.49 | 0.67 | 0.96 |
| **AlphaR1b** | 0.31 | 0.49 | 0.66 | 183 | 243 | 374 | 292 | 393 | 591 | 30 | 43 | 53 | 1.36 | 1.61 | 1.89 | 0.28 | 0.34 | 0.43 | 0.60 | 0.75 | 1.03 |
| **AlphaR1c** | 0.12 | 0.19 | 0.30 | 366 | 570 | 840 | 505 | 800 | 1302 | 28 | 45 | 58 | 0.99 | 1.45 | 1.85 | 0.27 | 0.42 | 0.65 | 0.55 | 0.72 | 1.13 |
| **AlphaR1d** | 0.30 | 0.46 | 0.64 | 183 | 257 | 394 | 294 | 411 | 636 | 26 | 42 | 51 | 1.35 | 1.62 | 1.90 | 0.28 | 0.35 | 0.43 | 0.60 | 0.77 | 1.12 |
| | **$r$ versus $B_{msy}/K$(shape parameter $n$) grids** | | | | | | | | | | | | | | | | | | | | |
| **ShapeR1** | 0.15 | 0.21 | 0.33 | 322 | 484 | 587 | 489 | 769 | 1250 | 30 | 43 | 53 | 1.15 | 1.68 | 2.41 | 0.23 | 0.39 | 0.63 | 0.61 | 0.75 | 1.06 |
| **ShapeR1b** | 0.32 | 0.50 | 0.72 | 163 | 232 | 371 | 323 | 469 | 761 | 32 | 43 | 52 | 1.57 | 2.06 | 2.57 | 0.20 | 0.28 | 0.39 | 0.62 | 0.75 | 1.02 |
| **ShapeR1e** | 0.11 | 0.17 | 0.26 | 311 | 483 | 784 | 413 | 641 | 1061 | 21 | 44 | 63 | 1.09 | 1.38 | 1.60 | 0.32 | 0.41 | 0.55 | 0.52 | 0.66 | 1.06 |
| **ShapeR1f** | 0.26 | 0.36 | 0.48 | 182 | 236 | 337 | 254 | 339 | 482 | 21 | 41 | 53 | 1.27 | 1.44 | 1.59 | 0.33 | 0.37 | 0.43 | 0.61 | 0.70 | 1.07 |
| | **Hawaii LL index** | | | | | | | | | | | | | | | | | | | | |
| **Hawaii1** | 0.15 | 0.22 | 0.34 | 304 | 424 | 615 | 83 | 186 | 529 | 20 | 30 | 52 | 0.22 | 0.42 | 1.33 | 0.42 | 1.78 | 3.21 | 0.62 | 1.10 | 1.62 |
| | **Max & Min catch** | | | | | | | | | | | | | | | | | | | | |
| **MaxCat1** | 0.26 | 0.40 | 0.58 | 209 | 302 | 464 | 298 | 439 | 739 | 34 | 47 | 58 | 1.19 | 1.49 | 1.76 | 0.42 | 0.53 | 0.70 | 0.83 | 1.01 | 1.43 |
| **MinCat1** | 0.26 | 0.40 | 0.59 | 124 | 183 | 292 | 187 | 282 | 469 | 19 | 28 | 33 | 1.30 | 1.56 | 1.86 | 0.32 | 0.42 | 0.55 | 0.71 | 0.85 | 1.23 |

Table 6. Grid comparison of key estimated parameters for combinations of $r$ and different surplus production, $B_{msy}/K$ (shape parameter, $n$). Values in the table are based on results of the base case, R1, R1b, Shape1, Shape3, ShapeR1, ShapeR1b, ShapeR1e and ShapeR1f.

| ***r*** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{msy}/K$ | 0.3 | 0.21 | 0.41 | 0.50 |
| | 0.47(Base) | 0.19 | 0.40 | 0.45 |
| | 0.6 | 0.17 | 0.33 | 0.36 |

| ***K*** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{msy}/K$ | 0.3 | 1613 | 908 | 773 |
| | 0.47(Base) | 1268 | 613 | 540 |
| | 0.6 | 805 | 437 | 393 |

| ***MSY*** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{msy}/K$ | 0.3 | 51 | 57 | 57 |
| | 0.47(Base) | 54 | 58 | 58 |
| | 0.6 | 58 | 61 | 61 |

| **Replacement yield** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{msy}/K$ | 0.3 | 43.4 | 43.9 | 43.3 |
| | 0.47(Base) | 45.8 | 42.5 | 42.1 |
| | 0.6 | 43.7 | 40.8 | 40.9 |

| $\boldsymbol{B_{2011}/B_{msy}}$ | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{msy}/K$ | 0.3 | 1.68 | 1.96 | 2.06 |
| | 0.47(Base) | 1.43 | 1.59 | 1.61 |
| | 0.6 | 1.38 | 1.43 | 1.44 |

| $\boldsymbol{F_{2011}/F_{msy}}$ | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{msy}/K$ | 0.3 | 0.39 | 0.29 | 0.28 |
| | 0.47(Base) | 0.42 | 0.35 | 0.35 |
| | 0.6 | 0.41 | 0.38 | 0.37 |

Table 7. Grid comparison of key estimated parameters for combinations of $r$ and $B_{init}/K$ (*alpha.b0*) prior mean. Values in the table are based on results of the base case, R1, R1b, Alpha1, Alpha1b, AlphaR1, AlphaR1b, AlphaR1c and AlphaR1d.

| ***r*** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{init}/K$ (*alpha.b0*) | 0.5 | 0.18 | 0.41 | 0.49 |
| | 0.8(Base) | 0.19 | 0.40 | 0.45 |
| | 1 | 0.19 | 0.39 | 0.46 |

| ***K*** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{init}/K$ (*alpha.b0*) | 0.5 | 1319 | 607 | 517 |
| | 0.8(Base) | 1268 | 613 | 540 |
| | 1 | 1212 | 627 | 547 |

| ***MSY*** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{init}/K$ (*alpha.b0*) | 0.5 | 55 | 58 | 59 |
| | 0.8(Base) | 54 | 58 | 58 |
| | 1 | 54 | 57 | 58 |

| **Replacement yield** | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{init}/K$ (*alpha.b0*) | 0.5 | 47.9 | 43.4 | 42.8 |
| | 0.8(Base) | 45.8 | 42.5 | 42.1 |
| | 1 | 44.6 | 42.8 | 41.8 |

| $B_{2011}/B_{msy}$ | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{init}/K$ (*alpha.b0*) | 0.5 | 1.36 | 1.59 | 1.61 |
| | 0.8(Base) | 1.43 | 1.59 | 1.61 |
| | 1 | 1.45 | 1.57 | 1.62 |

| $F_{2011}/F_{msy}$ | | *r* | | |
|---|---|---|---|---|
| | | 0.14 | 0.34(Base) | 0.43 |
| $B_{init}/K$ (*alpha.b0*) | 0.5 | 0.45 | 0.35 | 0.34 |
| | 0.8(Base) | 0.42 | 0.35 | 0.35 |
| | 1 | 0.42 | 0.36 | 0.34 |

Table 8. Bayes factors for alternative sensitivity runs. Bayes factors reflect the ratio of the probability of the blue shark (*Prionace glauca*) stock assessment data based on a sensitivity run to the probability of the data obtained from the base case.

| Category code | Category description | Run ID | Run description | Bayes factor |
|---|---|---|---|---|
| Shape | $B_{msy}/K$ (shape parameter $n$) | Base | $B_{msy}/K$ = 0.47 ($n$ = 1.71) | 1.00 |
| | | Shape1 | $B_{msy}/K$ = 0.30 ($n$ = 0.68) | 0.90 |
| | | Shape3 | $B_{msy}/K$ = 0.60 ($n$ = 3.39) | 0.54 |
| R1 | $r$ prior mean | Base | mean = 0.34 | 1.00 |
| | | R1 | mean = 0.14 | 0.13 |
| | | R1b | mean = 0.43 | 1.33 |
| R2 | $r$ prior SD | Base | SD = 0.3 | 1.00 |
| | | R2 | SD = 0.5 | 0.94 |
| | | R2b | SD = 0.7 | 0.89 |
| Alpha1 | $B_{init}/K$ (*alpha.b0*) prior mean | Base | mean = 0.8 | 1.00 |
| | | Alpha1 | mean = 0.5 | 1.13 |
| | | Alpha1b | mean = 1.0 | 0.86 |
| Alpha2 | $B_{init}/K$ (*alpha.b0*) prior SD | Base | SD = 0.5 | 1.00 |
| | | Alpha2 | SD = 0.7 | 0.94 |
| | | Alpha2b | SD = 0.9 | 0.91 |
| Min&MaxCat | Catch | Base | Base catch | 1.00 |
| | | MaxCat1 | Maximum catch scenario | 0.81 |
| | | MinCat1 | Minimum catch scenario | 0.23 |

Table 9. Decision table based on results of future projections for the base case, maximum and minimum blue shark (*Prionace glauca*) catch scenarios.

| Run ID | HCR | Total $C_{2011}$ | $B_{2011}$ / $B_{msy}$ | $F_{2011}$ / $F_{msy}$ | $C_{2011}$ / RepY | Total $C_{2016}$ | $B_{2016}$ / $B_{msy}$ | P($B_{2016}$ > $B_{msy}$) | $F_{2016}$ / $F_{msy}$ | $C_{2016}$ / RepY | Total $C_{2021}$ | $B_{2021}$ / $B_{msy}$ | P($B_{2021}$ > $B_{msy}$) | $F_{2021}$ / $F_{msy}$ | $C_{2021}$ / RepY | Total $C_{2031}$ | $B_{2031}$ / $B_{msy}$ | P($B_{2031}$ > $B_{msy}$) | $F_{2031}$ / $F_{msy}$ | $C_{2031}$ / RepY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Base** | **Status quo** | 32.54 | 1.59 | 0.35 | 0.75 | 40.64 | 1.55 | 1.00 | 0.45 | 0.93 | 40.64 | 1.59 | 1.00 | 0.45 | 0.94 | 40.64 | 1.58 | 0.99 | 0.44 | 0.95 |
| | **+20%** | 32.54 | 1.59 | 0.35 | 0.75 | 48.77 | 1.45 | 0.99 | 0.58 | 1.05 | 48.77 | 1.44 | 0.96 | 0.59 | 1.01 | 48.77 | 1.42 | 0.95 | 0.60 | 0.99 |
| | **-20%** | 32.54 | 1.59 | 0.35 | 0.75 | 32.51 | 1.65 | 1.00 | 0.34 | 0.79 | 32.51 | 1.71 | 1.00 | 0.33 | 0.84 | 32.51 | 1.72 | 1.00 | 0.33 | 0.83 |
| | $F_{2006-2010}$ | 32.54 | 1.59 | 0.46 | 0.75 | 38.45 | 1.55 | 1.00 | 0.46 | 0.91 | 40.00 | 1.57 | 0.99 | 0.46 | 1.03 | 42.92 | 1.55 | 0.99 | 0.46 | 1.37 |
| | **+20%** | 32.54 | 1.59 | 0.56 | 0.75 | 43.99 | 1.46 | 0.99 | 0.56 | 0.96 | 45.30 | 1.47 | 0.97 | 0.56 | 1.04 | 48.45 | 1.44 | 0.96 | 0.56 | 1.28 |
| | **-20%** | 32.54 | 1.59 | 0.37 | 0.75 | 32.24 | 1.63 | 1.00 | 0.37 | 0.85 | 33.84 | 1.68 | 1.00 | 0.37 | 1.03 | 36.42 | 1.65 | 1.00 | 0.37 | 1.54 |
| | $F_{msy}$ | 32.54 | 1.59 | 0.35 | 0.75 | 66.38 | 1.12 | na | 1.03 | 1.17 | 60.44 | 1.04 | na | 1.01 | 1.05 | 57.97 | 1.00 | na | 1.00 | 1.00 |
| **MaxCat1** | **Status quo** | 47.71 | 1.49 | 0.53 | 1.01 | 45.25 | 1.51 | 0.99 | 0.49 | 0.95 | 45.25 | 1.50 | 0.99 | 0.49 | 0.95 | 45.25 | 1.54 | 0.99 | 0.48 | 0.96 |
| | **+20%** | 47.71 | 1.49 | 0.53 | 1.01 | 54.30 | 1.41 | 0.97 | 0.64 | 1.06 | 54.30 | 1.34 | 0.88 | 0.66 | 1.02 | 54.30 | 1.34 | 0.89 | 0.67 | 1.01 |
| | **-20%** | 47.71 | 1.49 | 0.53 | 1.01 | 36.20 | 1.63 | 1.00 | 0.37 | 0.81 | 36.20 | 1.64 | 1.00 | 0.36 | 0.84 | 36.20 | 1.68 | 1.00 | 0.35 | 0.89 |
| | $F_{2006-2010}$ | 47.71 | 1.49 | 0.51 | 1.01 | 42.21 | 1.50 | 0.99 | 0.51 | 0.86 | 36.62 | 1.48 | 0.98 | 0.51 | 0.67 | 44.05 | 1.50 | 0.98 | 0.51 | 0.95 |
| | **+20%** | 47.71 | 1.49 | 0.61 | 1.01 | 47.83 | 1.41 | 0.98 | 0.61 | 0.93 | 40.46 | 1.37 | 0.96 | 0.61 | 0.72 | 48.78 | 1.39 | 0.94 | 0.61 | 0.96 |
| | **-20%** | 47.71 | 1.49 | 0.41 | 1.01 | 35.73 | 1.59 | 0.99 | 0.41 | 0.78 | 31.72 | 1.59 | 1.00 | 0.41 | 0.61 | 38.01 | 1.62 | 0.99 | 0.41 | 0.93 |
| | $F_{msy}$ | 47.71 | 1.49 | 0.53 | 1.01 | 68.61 | 1.10 | na | 1.03 | 1.14 | 62.18 | 1.01 | na | 1.02 | 1.03 | 60.88 | 1.01 | na | 1.00 | 1.02 |
| **MinCat1** | **Status quo** | 23.85 | 1.56 | 0.41 | 0.85 | 27.99 | 1.54 | 0.99 | 0.50 | 0.98 | 27.99 | 1.54 | 0.99 | 0.49 | 0.95 | 27.99 | 1.51 | 0.99 | 0.51 | 0.95 |
| | **+20%** | 23.85 | 1.56 | 0.41 | 0.85 | 33.59 | 1.43 | 0.98 | 0.64 | 1.08 | 33.59 | 1.36 | 0.94 | 0.67 | 1.03 | 33.59 | 1.30 | 0.84 | 0.70 | 1.02 |
| | **-20%** | 23.85 | 1.56 | 0.41 | 0.85 | 22.39 | 1.64 | 1.00 | 0.37 | 0.84 | 22.39 | 1.68 | 1.00 | 0.36 | 0.85 | 22.39 | 1.68 | 1.00 | 0.37 | 0.84 |
| | $F_{2006-2010}$ | 23.85 | 1.56 | 0.50 | 0.85 | 28.24 | 1.51 | 1.00 | 0.50 | 0.83 | 30.47 | 1.53 | 0.99 | 0.50 | 0.96 | 28.75 | 1.51 | 0.98 | 0.50 | 0.85 |
| | **+20%** | 23.85 | 1.56 | 0.60 | 0.85 | 31.95 | 1.43 | 0.99 | 0.60 | 0.90 | 33.60 | 1.42 | 0.96 | 0.60 | 0.98 | 31.38 | 1.40 | 0.94 | 0.60 | 0.88 |
| | **-20%** | 23.85 | 1.56 | 0.40 | 0.85 | 23.93 | 1.61 | 1.00 | 0.40 | 0.74 | 26.45 | 1.65 | 1.00 | 0.40 | 0.94 | 25.14 | 1.62 | 1.00 | 0.40 | 0.82 |
| | $F_{msy}$ | 23.85 | 1.56 | 0.41 | 0.85 | 42.33 | 1.11 | na | 1.03 | 1.17 | 38.13 | 1.04 | na | 1.01 | 1.04 | 36.65 | 1.00 | na | 1.00 | 1.00 |

FIGURES

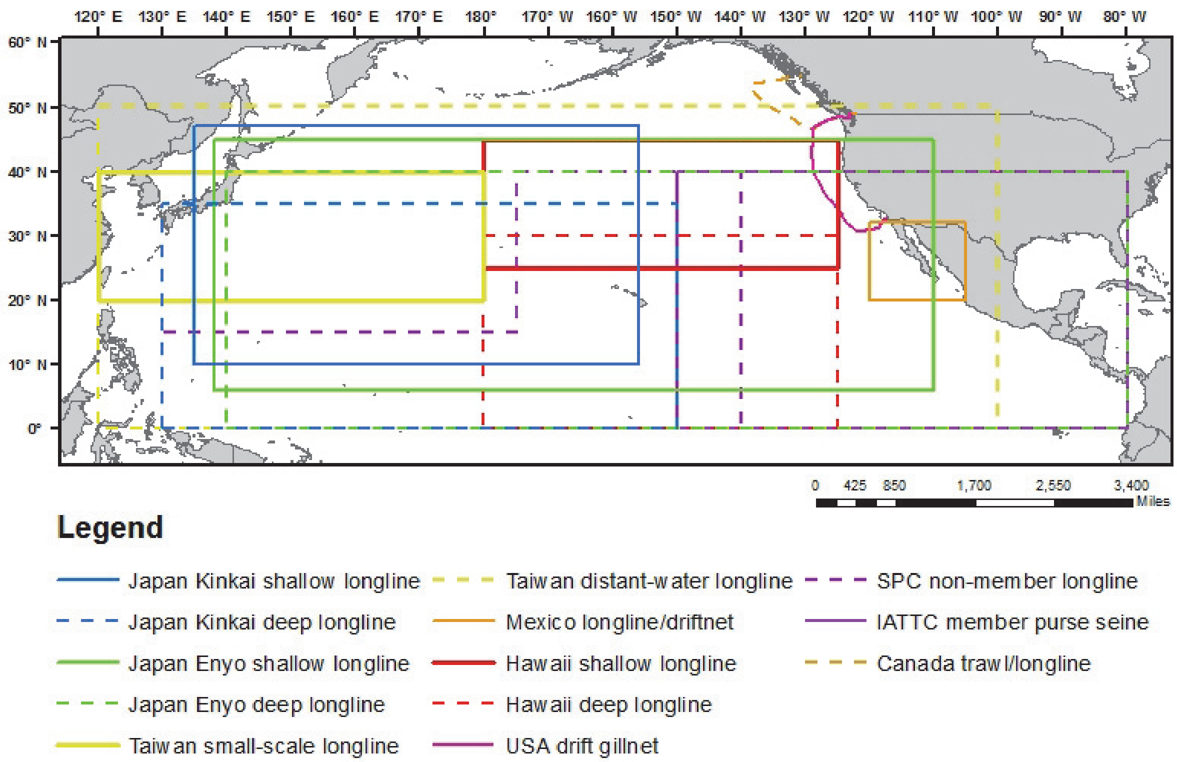


Figure 1. Blue shark (*Prionace glauca*) **s**tock boundaries and approximate spatial extent of the primary fisheries contributing catch for this assessment.

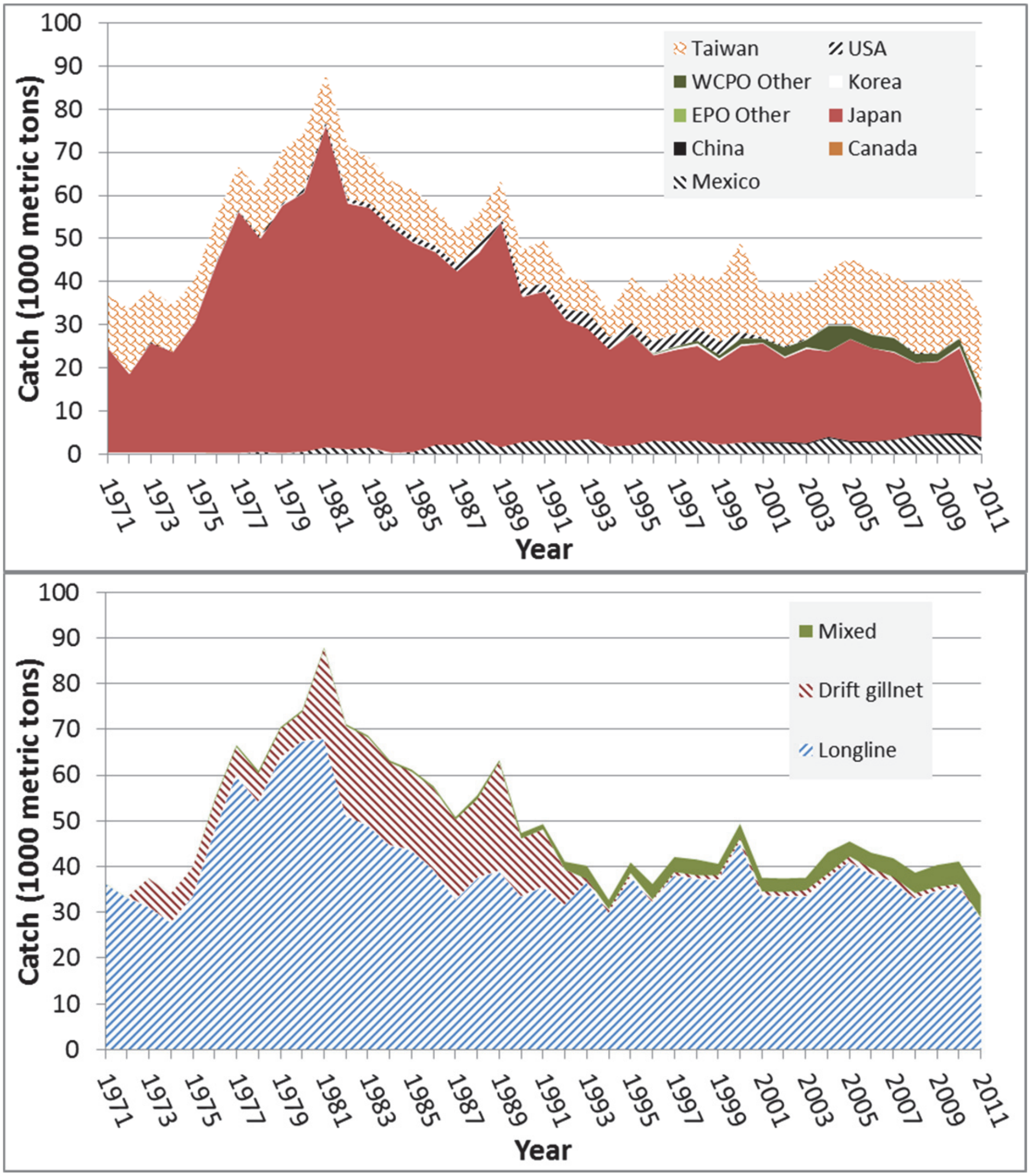


Figure 2. Total catch of blue sharks (*Prionace glauca*) in the North Pacific Ocean from 1971-2011 across all data sources. Top panel is broken down by nation when possible, or source of fishery data. Bottom panel is broken down by gear type. Longline includes deep, shallow, and coastal fisheries. Drift gillnet includes coastal and high seas fisheries. Mixed includes Mexico's small vessel artisanal fisheries which often fish both longline and gillnet, the medium vessel swordfish fisheries which also use both gear types, and the large vessel tuna longlines, and other small scale fisheries including Canadian troll, Japanese trap and bait fisheries and USA recreational fisheries.

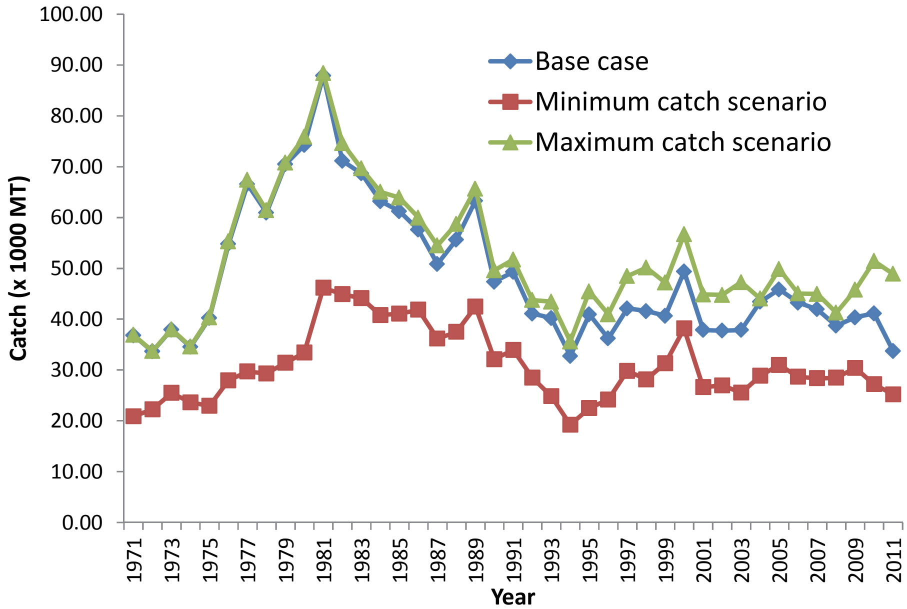


Figure 3. Comparison of total blue shark (*Prionace glauca*) catch used in the base case assessment with maximum and minimum catch scenario for sensitivity analyses.

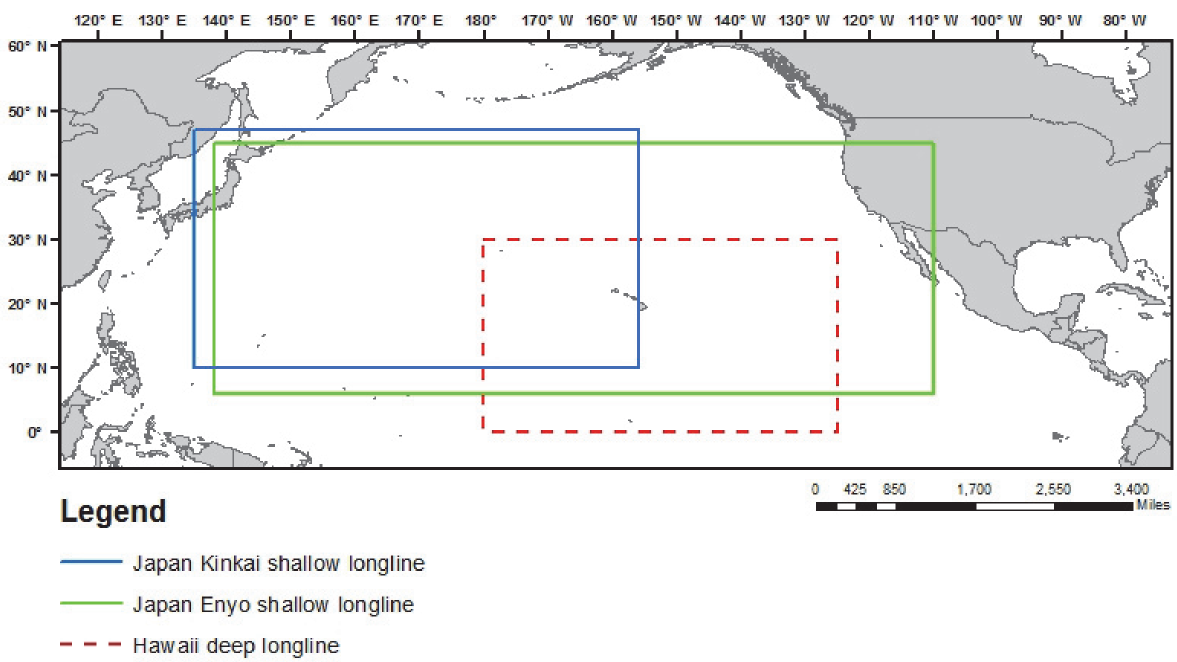


Figure 4. Spatial extent of fisheries used to derive abundance indices for base case and sensitivity analyses in the North Pacific Ocean blue shark (*Prionace glauca*) assessment.

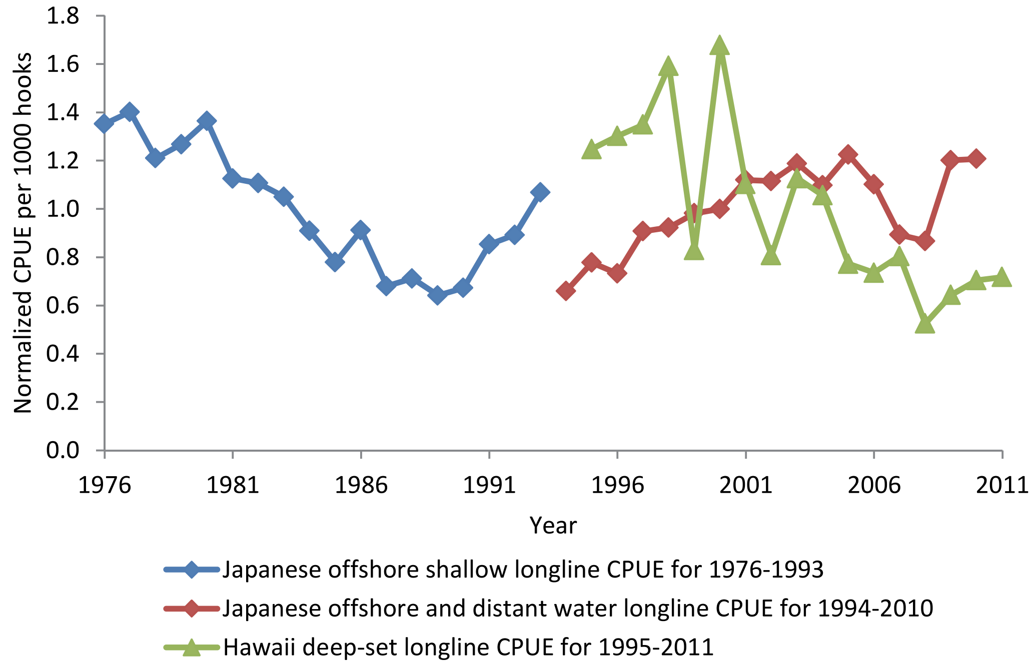


Figure 5. Abundance indices used in the North Pacific Ocean blue shark (*Prionace glauca*) stock assessment. BSP model was fitted to Japanese offshore shallow longline CPUE index (1976-1993 period, blue diamonds), and Japanese offshore and distant water longline CPUE index (1994-2010 period, red diamonds) in the base case. For a sensitivity run of alternative abundance index, Hawaii deep-set longline index (1995-2011 period, green triangles) was used instead of Japanese offshore and distant water longline index (1994-2010 period, red diamonds).

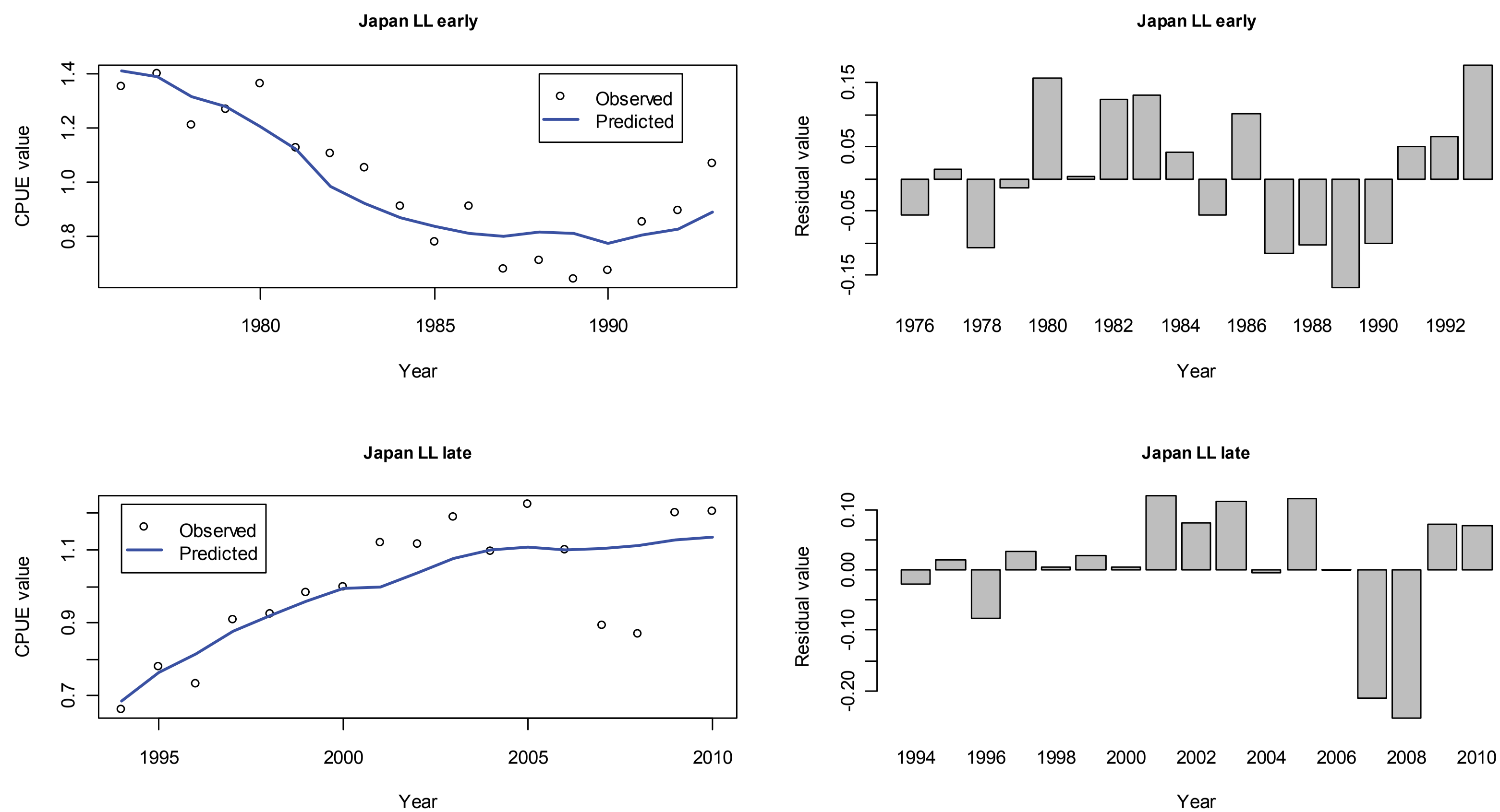


Figure 6. Model fits to the standardized CPUE indices used for the base case in the blue shark (*Prionace glauca*) stock assessment (left panels) and the residual plots (right panels). The blue solid lines are the model predicted values and the open circles are observed (data) values. Top and bottom panels correspond to Japanese longline indices for early (1976-1993) and late (1994-2010) periods, respectively.

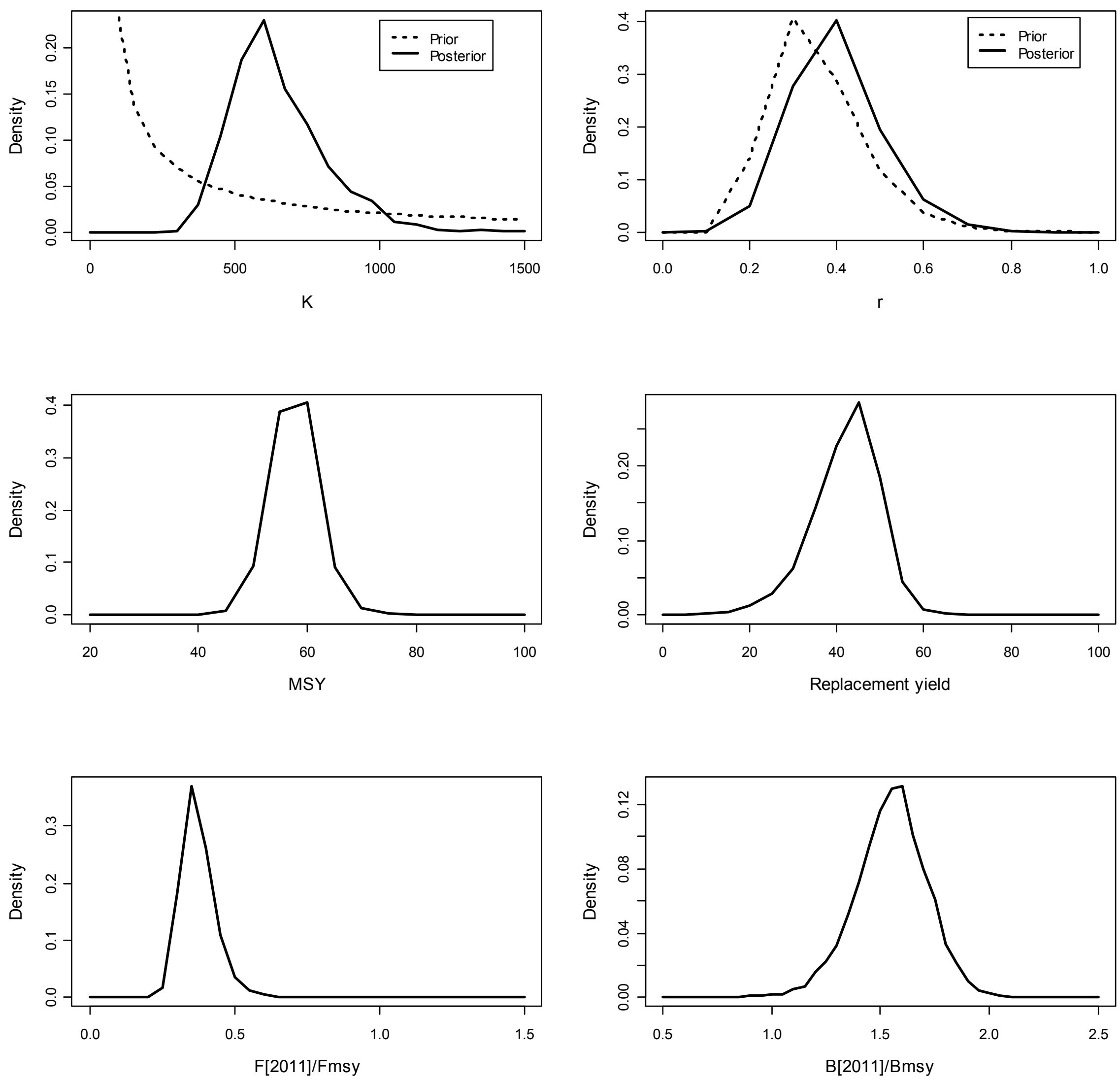


Figure 7. Marginal posterior distributions for carrying capacity ($K$), the maximum intrinsic rate of natural increase ($r$), maximum sustainable yield ($MSY$), replacement yield in 2011, the ratio of fishing mortality rate in 2011 to that at $MSY$ ($F_{2011}/F_{msy}$) and the ratio of stock biomass in 2011 to that at MSY ($B_{2011}/B_{msy}$) for blue shark (*Prionace glauca*).

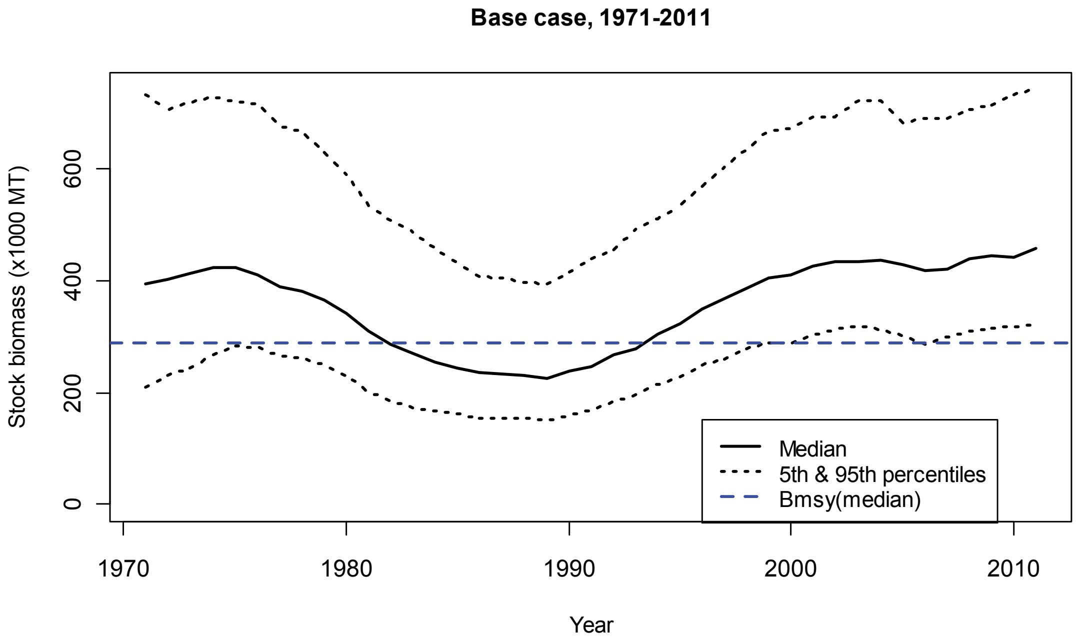


Figure 8. Median estimate and 90% confidence limits for the historical stock dynamics of North Pacific blue shark (*Prionace glauca*). The black solid and dotted lines represent the median, 10th and 90th percentiles, respectively. The blue dashed line indicates the median estimate for the biomass at maximum sustainable yield ($B_{msy}$).

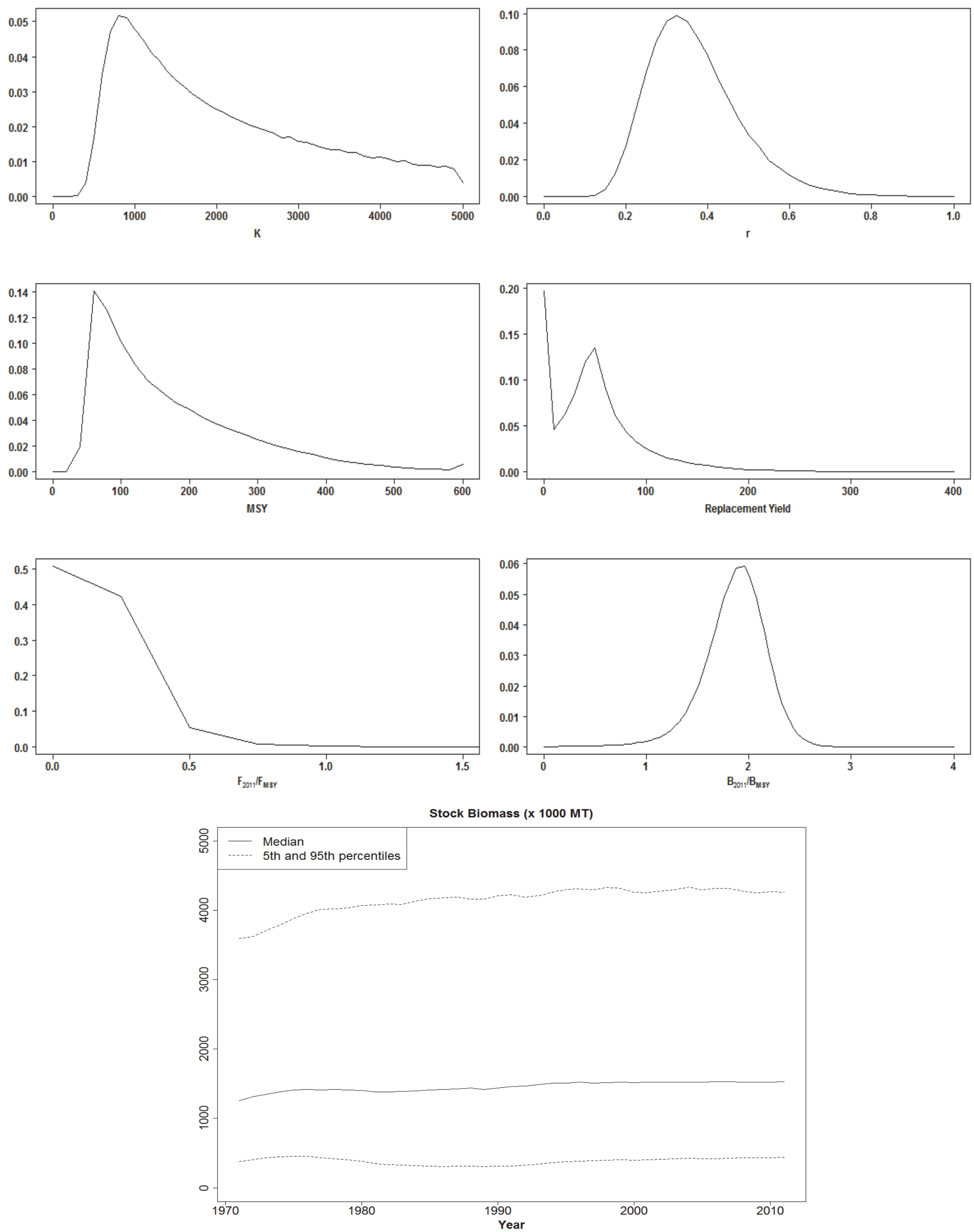


Figure 9. Results of running the base case model with priors only (excluding indices). Top two rows are posterior distributions for *K*, *r*, *MSY*, Replacement yield, $F_{2011}/F_{MSY}$, and $B_{2011}/B_{MSY}$; and bottom row is stock biomass with confidence intervals.

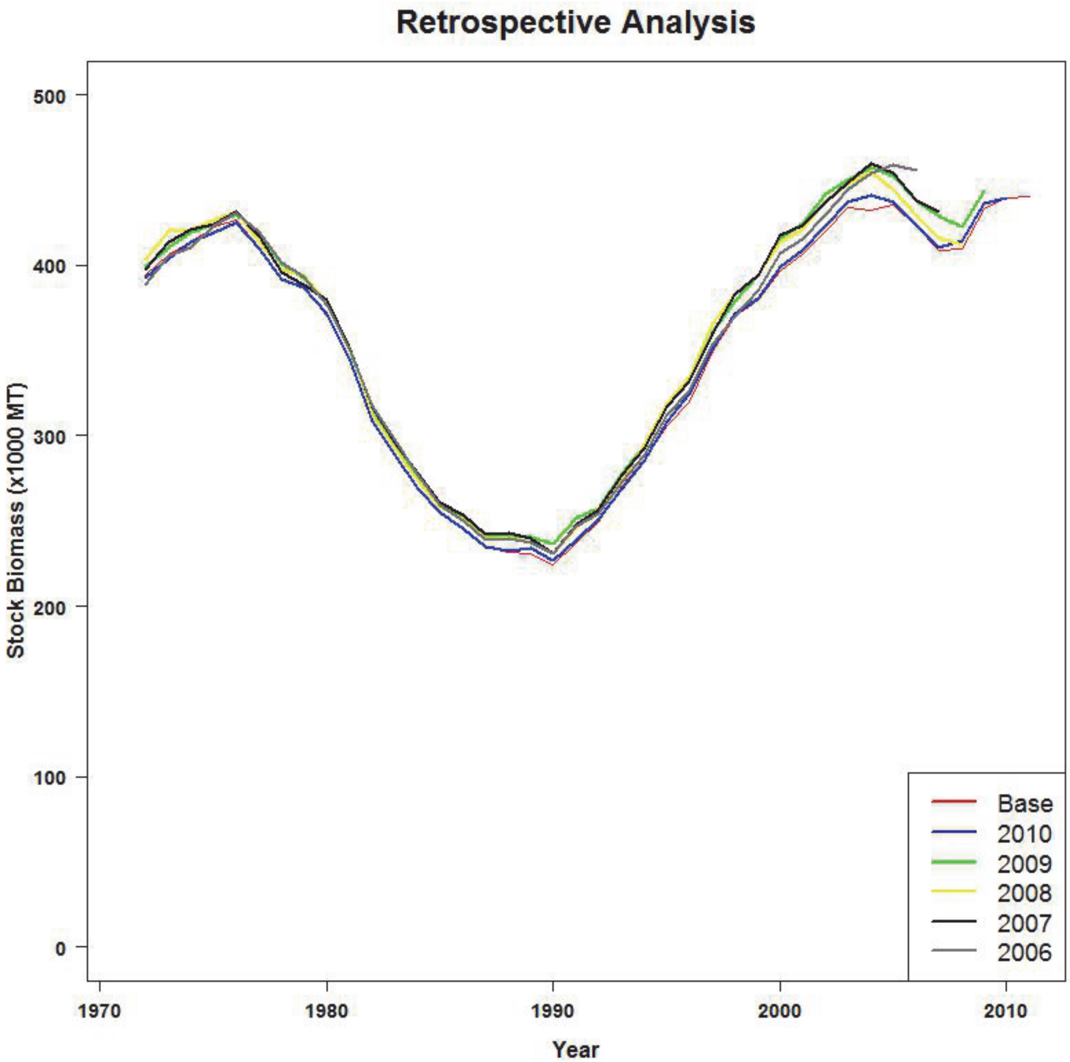


Figure 10. Comparison of historical blue shark (*Prionace glauca*) stock dynamics resulting from termination of the model in each of the five years prior to the base case time-series.

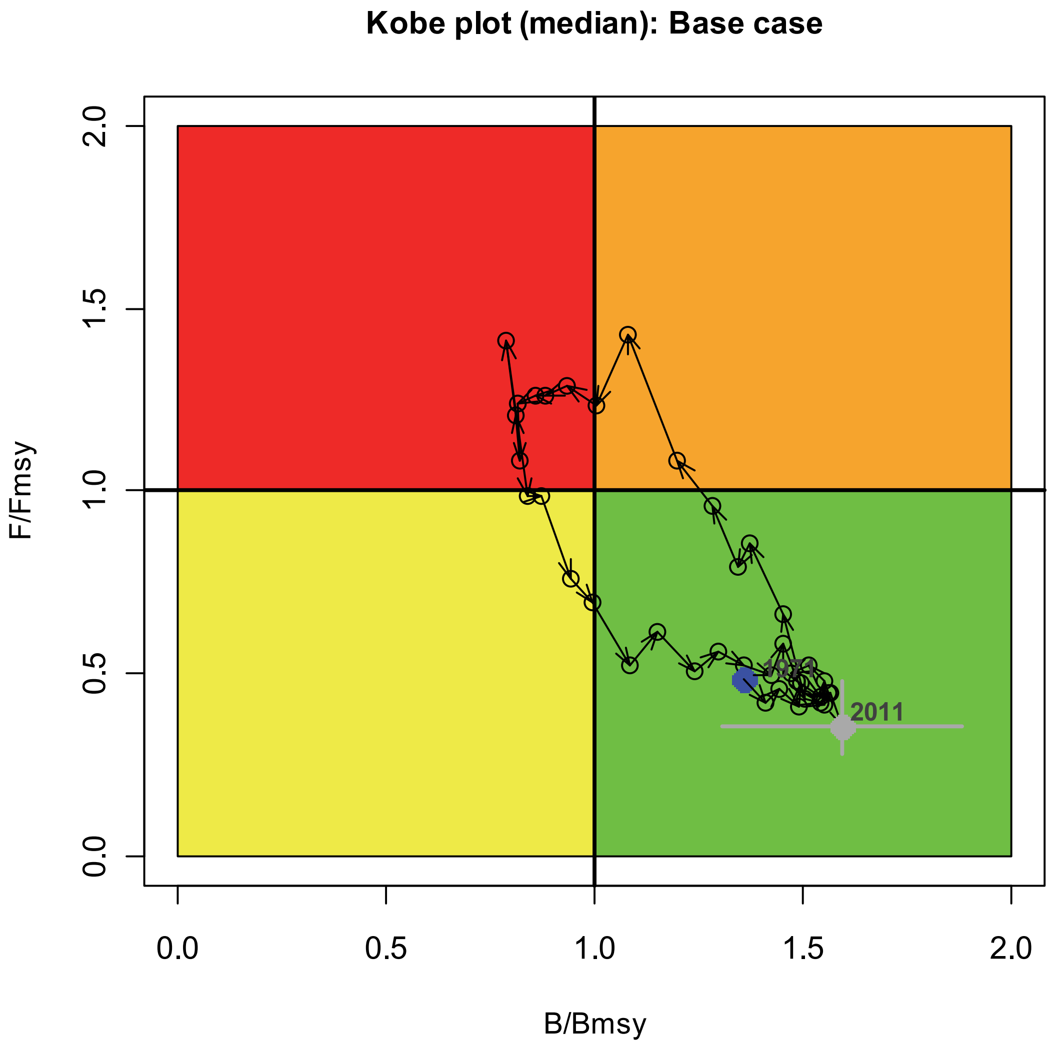


Figure 11. Kobe plot for the base case in the North Pacific Ocean blue shark (*Prionace glauca*) stock assessment. Kobe plot illustrates degrees of stock depletion (horizontal axis) and over-fishing (vertical axis). Colors represent the magnitude of risk of stock collapse green (safe) to red (high risk). The solid blue circle indicates the median estimate in 1971 (the start year of stock assessment calculation). The solid gray circle and its horizontal and vertical solid gray lines indicate the median and 90% confidence limits in 2011, respectively. The open black circles and connected solid black arrows are the medians in years between 1971 and 2011 and historical directions of stock status.

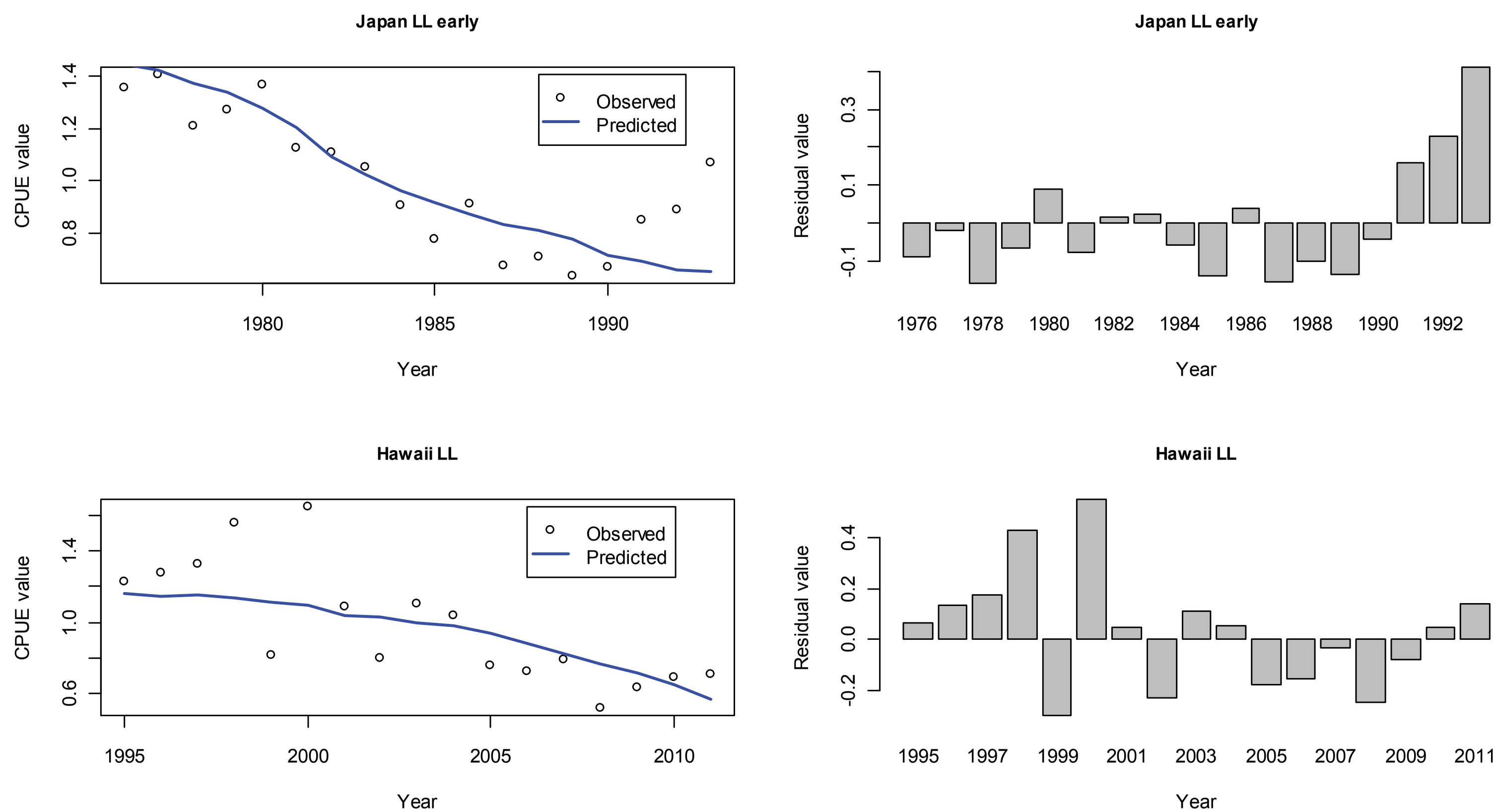


Figure 12. Model fits to the standardized CPUE indices used for the sensitivity run of alternative CPUE index (Hawaii deep-set longline index) in the blue shark (*Prionace glauca*) stock assessment (left panels) and the residual plots (right panels). The blue solid lines are the model predicted values and the open circles are observed (data) values. Top and bottom panels correspond to Japanese offshore shallow longline index for early (1976-1993) period (same as the base case) and Hawaii deep-set longline index for late (1995-2011) period (alternative index), respectively.

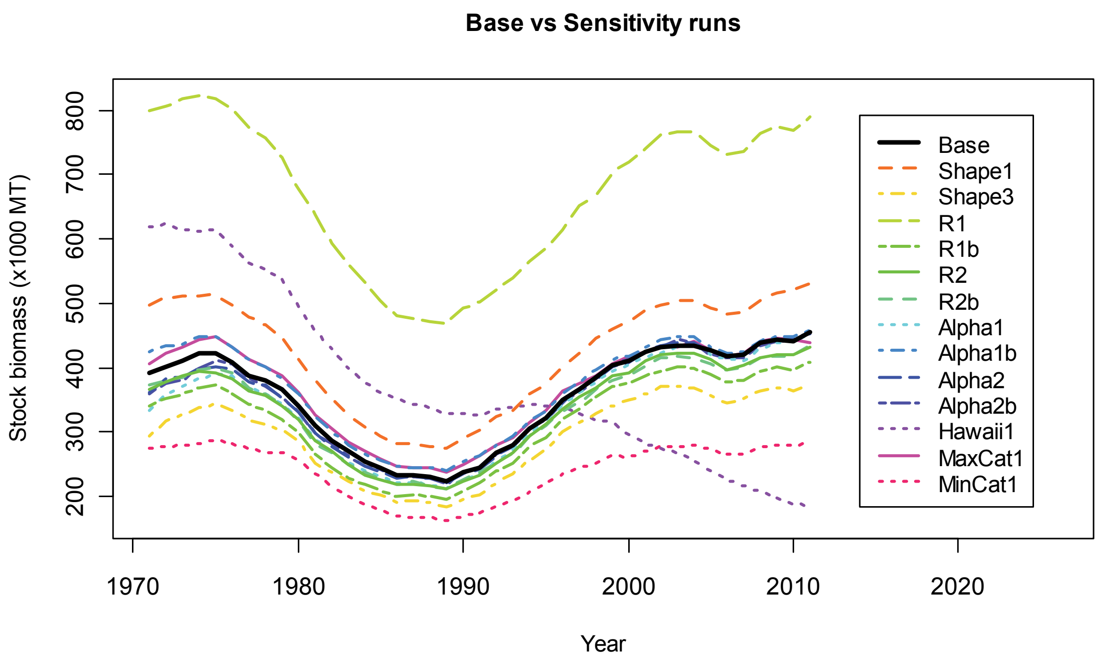


Figure 13. Comparison of median trajectories of historical blue shark (*Prionace glauca*) stock dynamics between the base case and sensitivity runs. See Table 3 for run identifiers and detailed descriptions of the sensitivity runs.

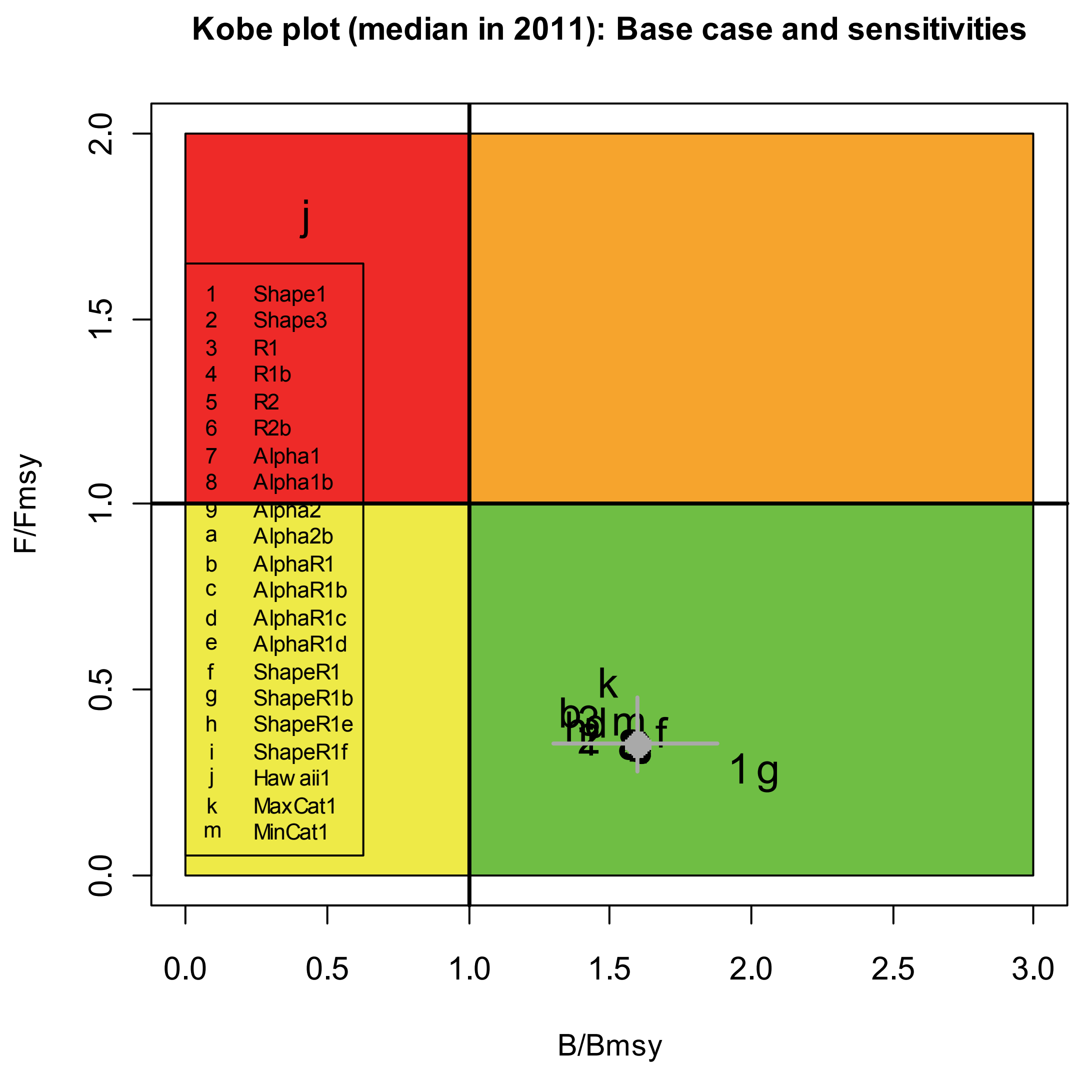


Figure 14. Kobe plot for the base case and sensitivity runs of the North Pacific Ocean blue shark (*Prionace glauca*) stock assessment. The solid gray circle and its horizontal and vertical solid gray lines indicate the median and 90% confidence limits in 2011 for the base case, respectively. Other different symbols (numbers and alphabets) indicate the median estimates in 2011 for various sensitivity runs. See Table 3 for run identifiers and detailed descriptions of the sensitivity runs.

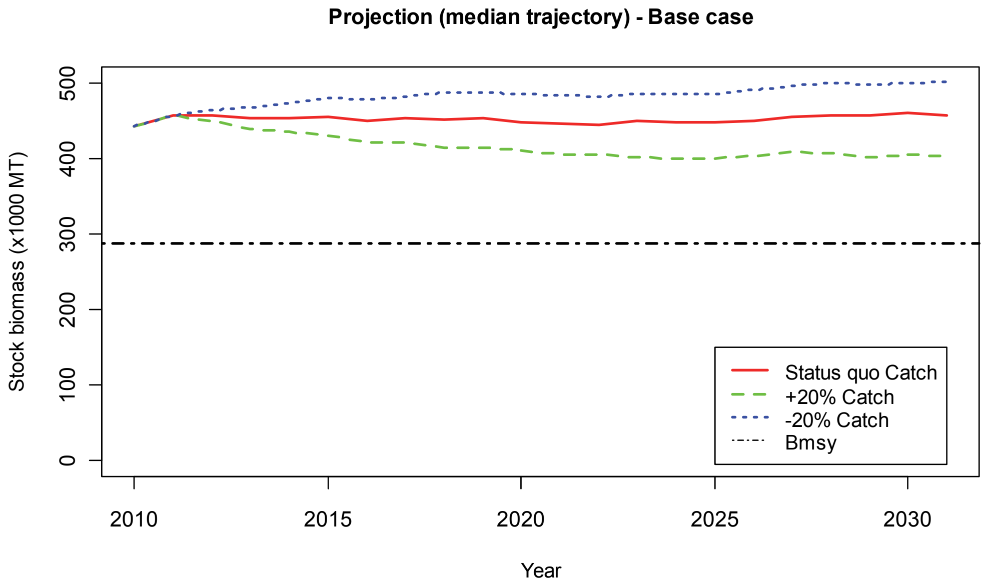


Figure 15. Comparison of future projected stock biomass (medians) of North Pacific Ocean blue shark (*Prionace glauca*) under different constant catch harvest policies (status quo, +20%, -20%) in the base case. Status quo catch was based on the average catch over recent 5 years of 2006-2010. The biomass level at the maximum sustainable yield, MSY ($B_{msy}$) was also plotted (black dot-dash line).

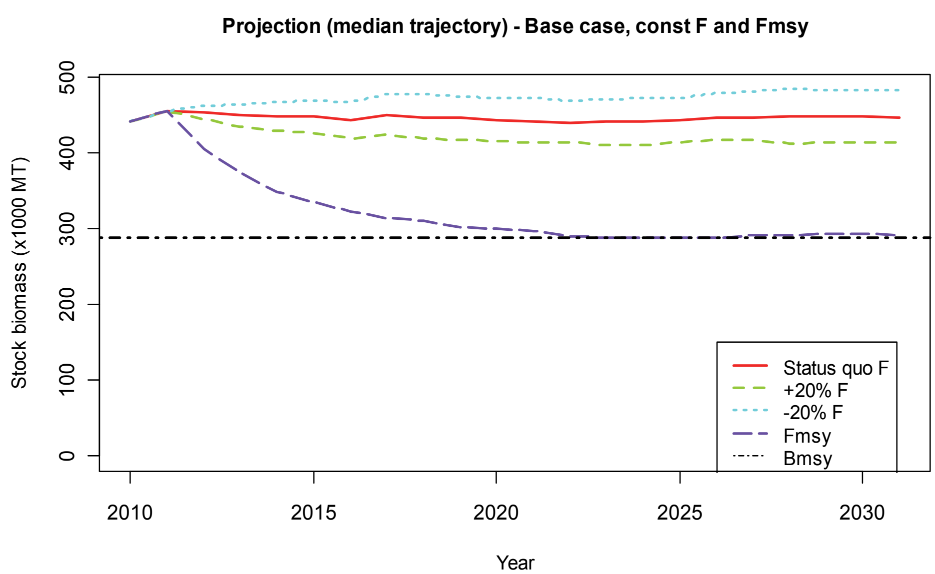


Figure 16. Comparison of future projected stock biomass (medians) of blue shark (*Prionace glauca*) under different constant *F* harvest policies (status quo, +20%, -20%, $F_{msy}$) in the base case. Status quo *F* was based on the average *F* over recent 5 years of 2006-2010. The biomass level at the maximum sustainable yield, MSY ($B_{msy}$) was also plotted (black dot-dash line).

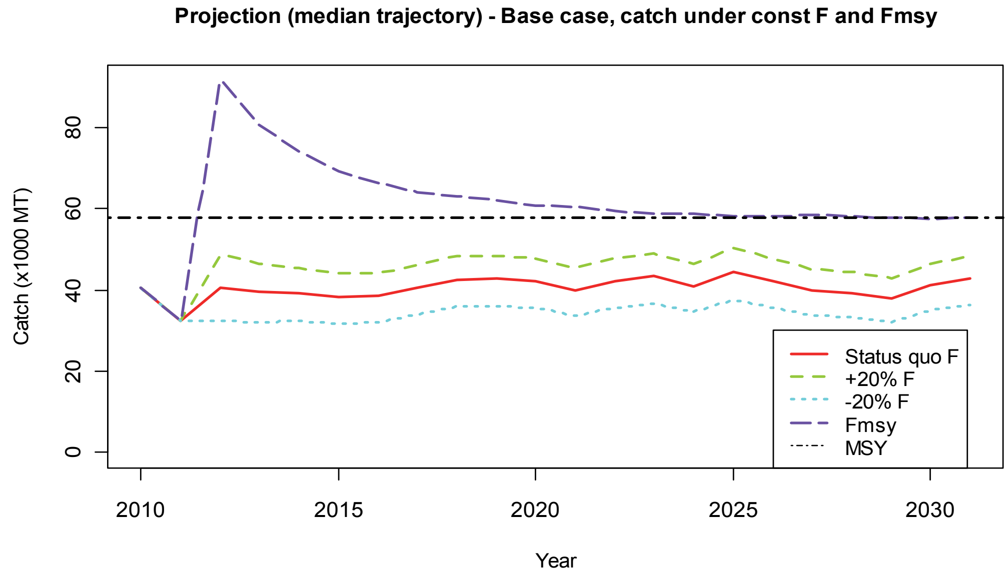


Figure 17. Comparison of future projected catches (medians) of North Pacific blue shark (*Prionace glauca*) under different constant *F* harvest policies (status quo, +20%, -20%, $F_{msy}$) in the base case. Status quo *F* was based on the average *F* over recent 5 years of 2006-2010. The maximum sustainable yield (MSY) level was also plotted (black dot-dash line).

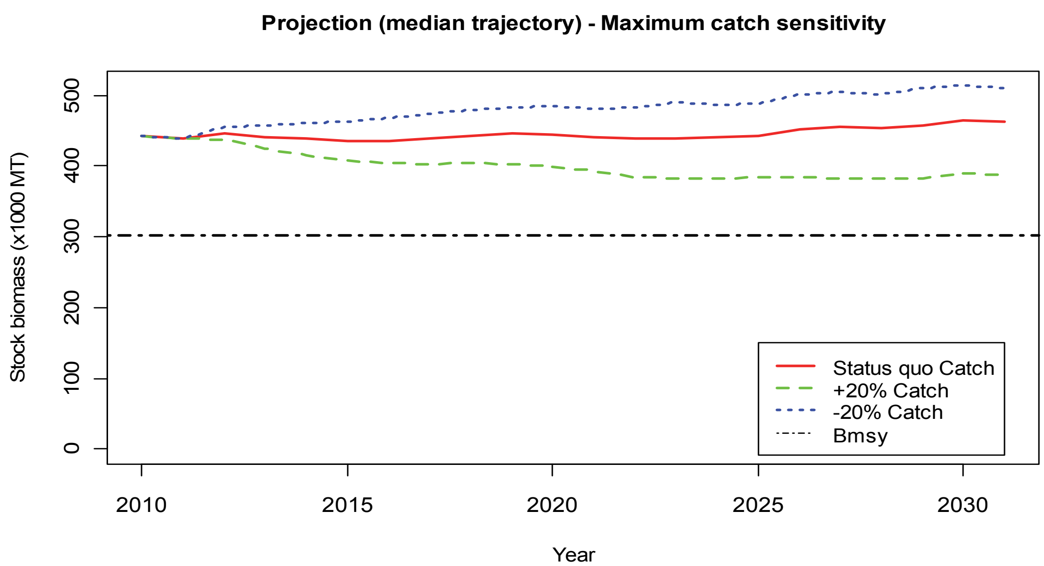


Figure 18. Comparison of future projected stock biomass (medians) of North Pacific blue shark (*Prionace glauca*) under different constant catch harvest policies (status quo, +20%, -20%) for the maximum catch scenario. Status quo catch was based on the average catch over recent 5 years of 2006-2010. The biomass level at the maximum sustainable yield, MSY ($B_{msy}$) was also plotted (black dot-dash line).

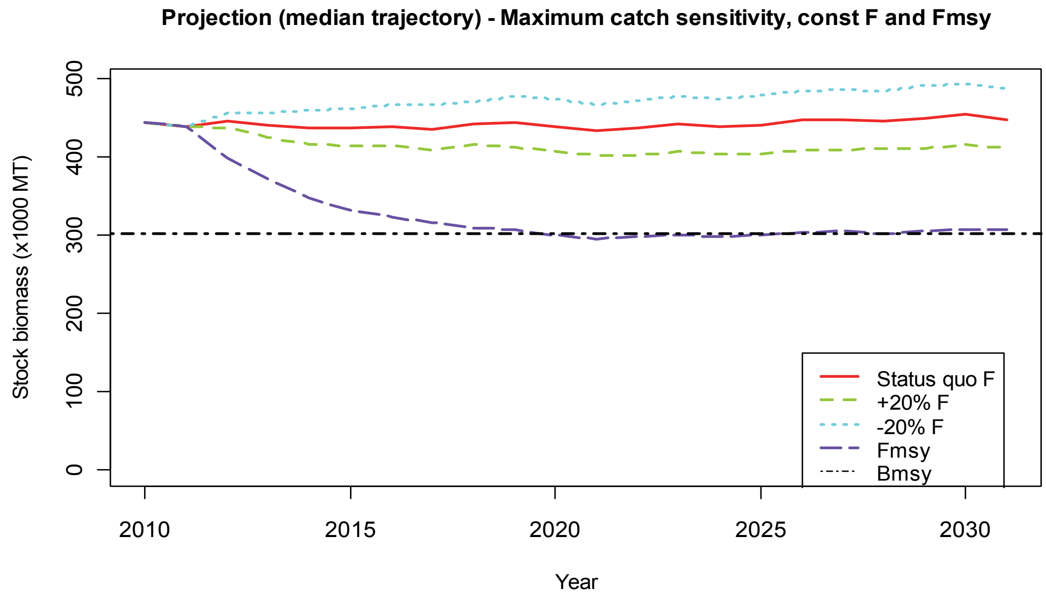


Figure 19. Comparison of future projected stock biomass (medians) of North Pacific blue shark (*Prionace glauca*) under different constant *F* harvest policies (status quo, +20%, -20%, $F_{msy}$) for the maximum catch scenario. Status quo *F* was based on the average *F* over recent 5 years of 2006-2010. The biomass level at the maximum sustainable yield, MSY ($B_{msy}$) was also plotted (black dot-dash line).

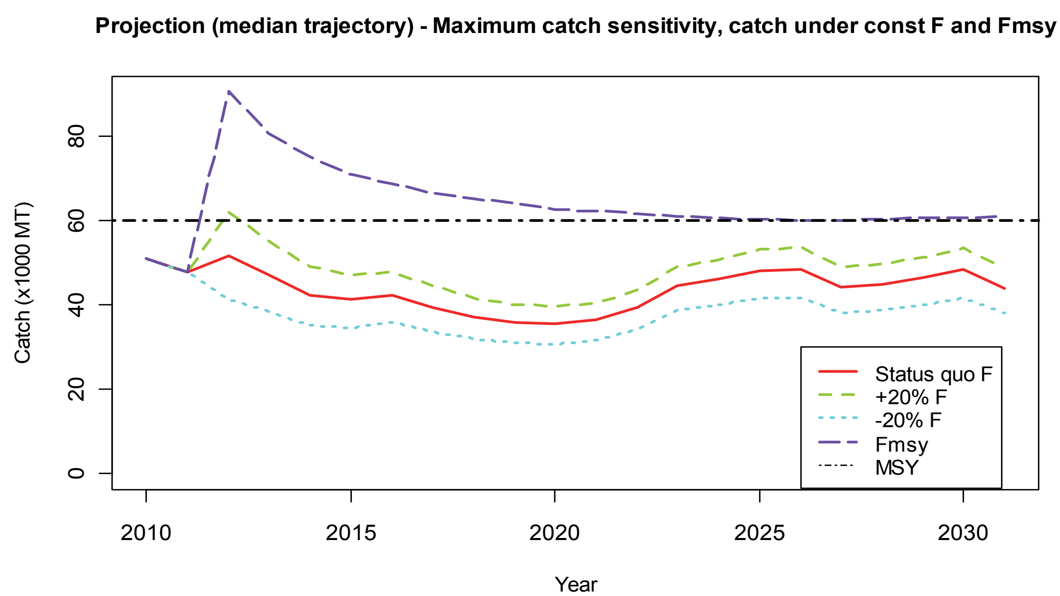


Figure 20. Comparison of future projected catches (medians) of North Pacific blue shark (*Prionace glauca*) under different constant *F* harvest policies (status quo, +20%, -20%, $F_{msy}$) for the maximum catch scenario. Status quo *F* was based on the average *F* over recent 5 years of 2006-2010. The maximum sustainable yield (MSY) level was also plotted (black dot-dash line).

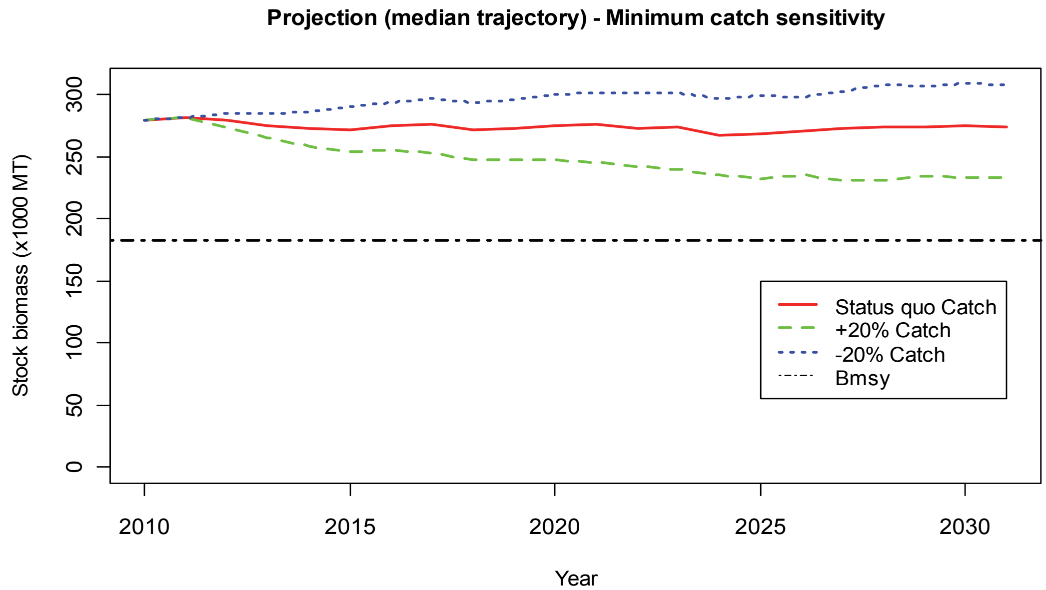


Figure 21. Comparison of future projected stock biomass (medians) of North Pacific blue shark (*Prionace glauca*) under different constant catch harvest policies (status quo, +20%, -20%) for the minimum catch scenario. Status quo catch was based on the average catch over recent 5 years of 2006-2010. The biomass level at the maximum sustainable yield, MSY ($B_{msy}$) was also plotted (black dot-dash line).

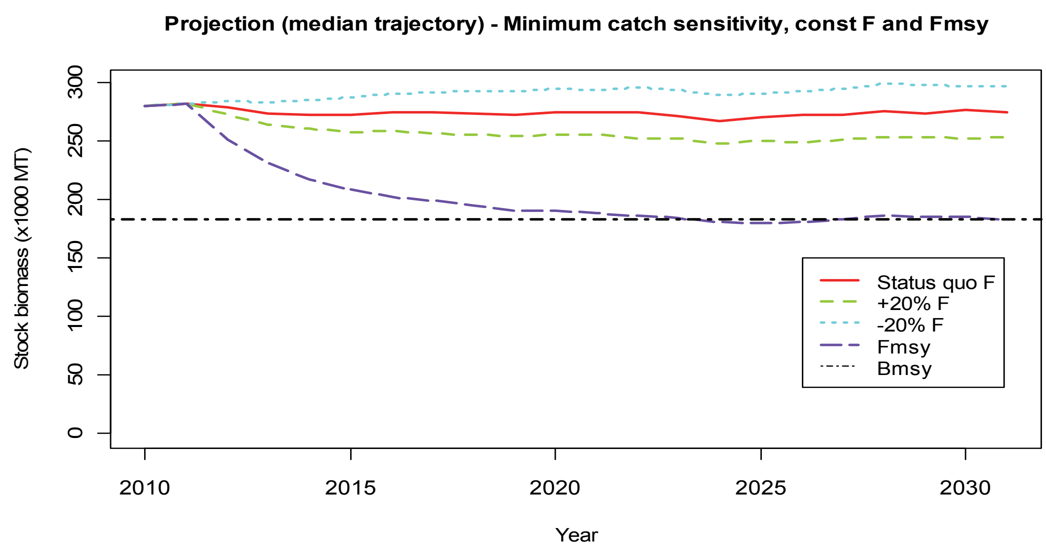


Figure 22. Comparison of future projected stock biomass (medians) of North Pacific blue shark (*Prionace glauca*) under different constant *F* harvest policies (status quo, +20%, -20%, $F_{msy}$) for the minimum catch scenario. Status quo *F* was based on the average *F* over recent 5 years of 2006-2010. The biomass level at the maximum sustainable yield, MSY ($B_{msy}$) was also plotted (black dot-dash line).

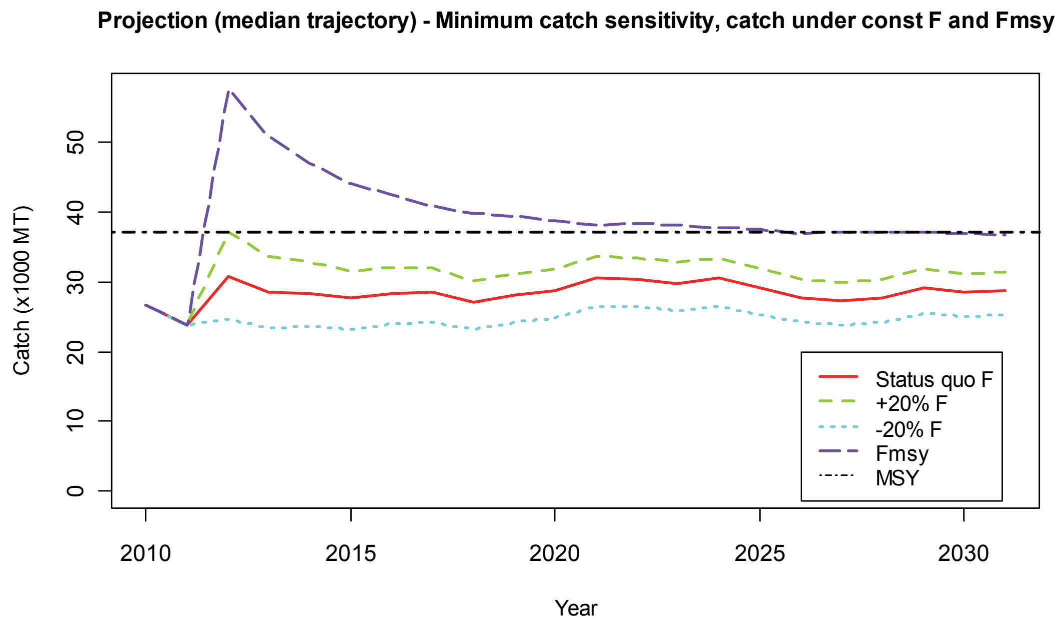


Figure 23. Comparison of future projected catches (medians) of North Pacific blue shark (*Prionace glauca*) under different constant *F* harvest policies (status quo, +20%, -20%, $F_{msy}$) for the minimum catch scenario. Status quo *F* was based on the average *F* over recent 5 years of 2006-2010. The maximum sustainable yield (MSY) level was also plotted (black dot-dash line).

# APPENDIX A: Model convergence diagnostics

Table A1. Diagnostic statistics for model convergence.

| Diagnostic statistics | Base | Shape1 | Shape3 | R1 | R1b | R2 | R2b | Alpha1 | Alpha1b | Alpha2 | Alpha2b |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Draws retained | 1993652 | 1351224 | 1589363 | 3146717 | 2453224 | 2384559 | 2061901 | 1736874 | 2518178 | 1747493 | 1964775 |
| CV(weight) | 35.91 | 29.93 | 47.84 | 48.29 | 36.08 | 37.19 | 36.68 | 42.03 | 38.15 | 41.48 | 43.35 |
| CV(likelihood*prior) | 262.26 | 143.34 | 254.30 | 223.30 | 269.49 | 275.83 | 182.25 | 190.98 | 249.23 | 193.74 | 211.96 |
| %maximum weight | 0.67 | 0.90 | 0.97 | 0.91 | 0.84 | 0.78 | 0.61 | 1.32 | 0.78 | 1.16 | 1.24 |

| Diagnostic statistics | AlphaR1 | AlphaR1b | AlphaR1c | AlphaR1d | ShapeR1 | ShapeR1b | ShapeR1e | ShapeR1f | Hawaii1 | MaxCat1 | MinCat1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Draws retained | 6894854 | 2087309 | 2315834 | 2448469 | 4435377 | 1590542 | 2080921 | 2049504 | 2198397 | 1598726 | 2895077 |
| CV(weight) | 75.80 | 39.89 | 48.83 | 36.22 | 73.08 | 31.10 | 49.38 | 44.46 | 47.81 | 43.64 | 58.88 |
| CV(likelihood*prior) | 180.24 | 241.79 | 210.96 | 216.15 | 224.59 | 137.24 | 243.90 | 362.35 | 302.47 | 173.19 | 288.66 |
| %maximum weight | 1.17 | 0.51 | 1.51 | 0.86 | 0.87 | 0.57 | 0.88 | 0.82 | 1.19 | 0.95 | 1.62 |

APPENDIX B: Input files

<u>Input file defining setup and parameters for base case model – 'inputs_NPBS_Base_run1.txt'</u>

```
"NPBS, Base case run 1 Apr 17, 2013"
"NPBS, Base run1, Catch(v130416), pe sigma 0.xx, Catchx000t, index CVo + CVp"
"files"
NPBS_Base_run1,run_identifier
1,histogram_file_name_extension
D:\DFO\ISC2013-NPBS\output\param_NPBS_Base_run1.out,filparin$
D:\DFO\ISC2013-NPBS\output\param_NPBS_Base_run1.out,filparout$
D:\DFO\ISC2013-NPBS\data\index_NPBS_Base.csv,cpue1f$
D:\DFO\ISC2013-NPBS\data\catch_NPBS_Base.csv,catf$
D:\DFO\ISC2013-NPBS\data\rec_ef_v1.csv,tbcef$
D:\DFO\ISC2013-NPBS\data\rec_c_v2.csv,tbcbcf$
D:\DFO\ISC2013-NPBS\data\seals_v11.csv,sealsf$
D:\DFO\ISC2013-NPBS\data\seal_diet_v11.csv,seal_dietf$
"General inputs"
1,bayesian
1,fletcher
0,F_iterate
0, impfunc
0,isetcov
1,expand_imp
25,degf
8,iwted
2,nind
1976,ifyrdata%
2011,iendyrdata%
1971,ifyr
1971,ifyrobscat
2011,icur
"Parameter inputs"
0,estn
0,ltransn
0,aminn
0,amaxn
1,estr
1,ltransr
0.001,aminr
1.0,amaxr
0,estcat0
1,ltranscat0
10,amincat0
5000,amaxcat0
1,estk
```

1,ltransk
50,aminK
2000,amaxk
1.0,estab0
1,ltransab0
0.001,aminab0
1.0,amaxab0
0,ltransig
0,aminsig
0,amaxsig
1,estq
1,ltransq
0.000000001,aminq
2,amaxq
"Set up projections"
1000, isims
3,npol
0, 40.64
0, 48.77
0, 32.51
1,iDoCIy
0.05,lci
0.95,uci
0, binvar
0 ,lowbin
0, binwidth
1, ibins
5, tyr1
10, tyr2
20, ihz
1971,refyear
"Set up priors"
0.8,alphamean
0.5,alphasd
0,catmean
0,catsd
0,sigmaprior
0,sigmamed
0,sigmasd
1,rprior
0.34,armean
1.71250393,anmean
0,avarn
0.09,avarr
0,acovrn
0,tdegf

1,logKprior
0, qprior
0.00, qincmean
1971, qinc_start_yr
1971, sigey_start_yr
0.05, sigey
-4,aminey
4,amaxey
1, catch_sens
100, fcur_prior_sd
0.6, r_imp_fn_cv
0.8, K_imp_fn_cv
0.003,rec_imp_fn_cv
0.2,hseal_imp_fn_cv
0.2,stell_imp_fn_cv
0.2,calsl_imp_fn_cv
0.2,elseal_imp_fn_cv
0.7, alpha_imp_fn_cv
-0.01,cor_k_r
-0.01, cov_K_alpha
0, estrecq
0.1, sigmarecc
0, ltranstbc
0.000000001,amintbc
0.5,amaxtbc
0, esthsealq
0.1, sigmahseal
1, ltransseal
0.0000000001,aminhseal
1,amaxhseal
0, eststellq
0.1, sigmastell
1, ltransstell
0.0000000001,aminstell
1,amaxstell
0, estcalsl
0.1, sigmacalsl
1, ltranscalsl
0.00000001,amincalsl
1,amaxcalsl
0, estelseal
0.1, sigmaelseal
1, ltranselseal
0.0000000001,aminelseal
1,amaxelseal
0.5, rho

```
0.00, natM
0, pred_init
0, informativeq
ccccccccccccccccccccccccccHISTOGRAM
0, akmin
1500, akmax
75, deltaK
0, BBegmin
4050,Bbegmax
100, deltaBbeg
20, MSYmin
100, MSYmax
5, deltaMSY
0, Bcmin
4005, BCmax
100, deltaBC
0, Bmmin
2005, Bmmax
100, deltaBm
0, repymin
100, repymax
5, deltarepy
0, pmin
1.55, pmax
0.025, deltap
0, qmin
1.5, qmax
0.05, deltaq
0.5, BcBmmin
2.5, BcBmmax
0.05, deltaBcBm
0, rmin
1.0, rmax
0.1, deltar
"x 000t", unitsb$
ccccccccccccccccccccScreenPlots
1, amaxbiop
0.5, amaxcatp
ccccccccccccccccccccccccccIMPORTANCE_SAMPLES
7000,nsims
1000, nsims2
end
```

Input file defining catch for base case model – ‘catch_NPBS_Base.csv’

```
1971,36.836
1972,33.671
1973,37.941
1974,34.550
1975,40.243
1976,54.785
1977,66.562
1978,60.952
1979,70.485
1980,74.246
1981,87.883
1982,71.147
1983,68.671
1984,63.197
1985,61.228
1986,57.591
1987,50.846
1988,55.644
1989,63.290
1990,47.376
1991,49.306
1992,41.090
1993,39.936
1994,32.544
1995,40.797
1996,36.010
1997,41.874
1998,41.297
1999,40.402
2000,48.991
2001,37.516
2002,37.334
2003,37.458
2004,42.546
2005,45.277
2006,42.606
2007,41.230
2008,38.580
2009,40.101
2010,40.685
2011,32.536
```

Input file defining abundance indices for base case model – 'index_NPBS_Base.csv'

```
1,1976,1.3521566,0.15,0,0
1,1977,1.4020387,0.15,0,0
1,1978,1.2099306,0.15,0,0
1,1979,1.2679296,0.15,0,0
1,1980,1.3644946,0.15,0,0
1,1981,1.1263064,0.15,0,0
1,1982,1.1069344,0.15,0,0
1,1983,1.0503551,0.15,0,0
1,1984,0.9088924,0.15,0,0
1,1985,0.7789571,0.15,0,0
1,1986,0.9115693,0.15,0,0
1,1987,0.6803548,0.15,0,0
1,1988,0.7117925,0.15,0,0
1,1989,0.6418145,0.15,0,0
1,1990,0.6724505,0.15,0,0
1,1991,0.85308,0.15,0,0
1,1992,0.892452,0.15,0,0
1,1993,1.068491,0.15,0,0
2,1994,0.6592668,0.14,0,0
2,1995,0.7777286,0.14,0,0
2,1996,0.7325144,0.14,0,0
2,1997,0.9079569,0.14,0,0
2,1998,0.9226145,0.14,0,0
2,1999,0.9819756,0.14,0,0
2,2000,0.999922,0.14,0,0
2,2001,1.1202357,0.14,0,0
2,2002,1.1150713,0.14,0,0
2,2003,1.1883627,0.14,0,0
2,2004,1.0980145,0.14,0,0
2,2005,1.224987,0.14,0,0
2,2006,1.1018498,0.14,0,0
2,2007,0.8929145,0.14,0,0
2,2008,0.8671182,0.14,0,0
2,2009,1.2017942,0.14,0,0
2,2010,1.2076735,0.14,0,0
```