Annex 12

STOCK ASSESSMENT OF ALBACORE TUNA IN THE NORTH PACIFIC OCEAN IN 2017

REPORT OF THE ALBACORE WORKING GROUP

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

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EXECUTIVE SUMMARY

Stock Identification and Distribution: The north Pacific albacore tuna (*Thunnus alalunga*) stock area consists of all waters in the Pacific Ocean north of the equator to 55°N. All available fishery data from this area were used for the stock assessment, assuming that there is instantaneous mixing of albacore on a quarterly basis, i.e., a single well-mixed stock.

Major changes from the 2014 assessment: There were three major changes to the base case model compared to the previous assessment in 2014. **1**) Most importantly, a new procedure was used to standardize the Japanese longline abundance index (1996 – 2015) used to indicate trends in adult albacore abundance and the results represent a substantial improvement relative to 2014 and earlier assessments. This new index had good contrast and, based on Age-Structured Production Model (ASPM) diagnostic analyses, informative on both population trend and scale. **2**) The start year of the base case model was changed from 1966 (in 2014) to 1993 (in 2017). This change eliminated the influence of poorly fit size composition data from the Japanese longline fleets in 1975 – 1992, and eliminated the conflict between these size composition data and the primary adult albacore indices. **3**) In previous assessments, the instantaneous rate of natural mortality (M) was assumed to be 0.3 y^{-1} for both sexes at all ages. The basis for this assumption was reviewed and found to be poorly supported. Sex-specific M-at-age vectors were developed from a meta-analysis, with a sex-combined M that scaled with size for ages 0-2, and sex-specific M fixed at 0.39 and 0.48 y^{-1} for age-3+ males and females, respectively.

Catches: During the modeling period (1993-2015), the total reported catch of north Pacific albacore reached a peak of 119,300 t in 1999 and then declined in the early 2000s, followed by a recovery in later years with catches fluctuating between 68,900 and 93,100 t in recent years (2010-2015) (Fig. ES1). Surface gears (troll, pole-and-line), which primarily harvest juvenile albacore, have accounted for approximately twice as much albacore catch as longline gear (Fig. ES2).

Data and Assessment: All north Pacific albacore catch and size composition data from ISC member countries (Canada, China, Chinese Taipei, Japan, Korea, and USA) and non-member countries were compiled for the assessment. Coherent fishery definitions, especially for the Japan longline and pole-and-line fisheries, improved model fits to the data and model diagnostics. Thirteen relative abundance indices (standardized catch-per-unit-effort) were provided by Japan, USA, and Chinese Taipei. Based on a thorough review of all fishery data and preliminary model runs, the Albacore Working Group (ALBWG) fitted the base case model to one abundance index, the Japanese longline index (S1) from the fleet operating south of 30°N and west of 160 °E (1996-2015). The S1 index was chosen because it represented the best information on trends for the adult age-classes of female albacore, had good contrast, and the results of ASPM analyses provided evidence that the S1 index was informative on both population trend and scale.

The north Pacific albacore tuna stock was assessed using a length-based, age-, and sex-structured Stock Synthesis (SS Version 3.24AB) model over the 1993-2015 period. Sex-specific growth curves from the 2014 assessment were used because of evidence of sexually dimorphic growth, with adult males attaining a larger size-at-age than females after maturity. Sex-specific M-at-age vectors were developed from a meta-analysis, with a sex-combined M that scaled with size for ages 0-2, and sex-specific M fixed at 0.48 and 0.39 y^{-1} for age-3+ females and males, respectively. The steepness of the Beverton-Holt stock-recruitment relationship was assumed to be 0.9, based on two prior analyses. The assessment model was fitted to the S1 index (1996-2015) and all representative size composition data in a likelihood-based statistical framework. All fleets were assumed to have dome-shaped length selectivity, and age-based selectivity for ages 1-5 was also estimated for

surface fleets (troll and pole-and-line) to address age-based changes in juvenile albacore availability and movement. Selectivity was assumed to vary over time for fleets with important changes in fishing operations. Maximum likelihood estimates of model parameters, derived outputs, and their variances were used to characterize stock status. Several sensitivity analyses were conducted to evaluate changes in model performance or the range of uncertainty resulting from changes in model parameters, including natural mortality, stock-recruitment steepness, starting year, selectivity estimation, variability of size-at-age and weighting of size composition data.

An age-structured production model diagnostic analysis, showed that the estimated catch-at-age and fixed productivity parameters (growth, mortality and stock-recruitment relationship without annual recruitment deviates) were able to explain trends in the S1 index. Based on these findings, the ALBWG concluded that the base case model was able to estimate the stock production function and the effect of fishing on the abundance of the north Pacific albacore stock. The link between catch-at-age and the S1 index adds confidence to the data used, and represents a major improvement in the 2017 assessment of the north Pacific albacore stock. Due to the moderate exploitation levels relative to the productivity, the production function was weakly informative about north Pacific albacore stock size, resulting in asymmetric uncertainty in the absolute scale of the stock, with more uncertainty in the upper limit of the stock than the lower limit. It is important to note that the primary aim of estimating the female spawning biomass (SSB) in this assessment was to determine if the estimated SSB was lower than the limit reference point (i.e., determine whether the stock is in an overfished condition). Since the lower bound is better defined, it adds confidence to the ALBWG's evaluation of stock condition relative to the limit reference point.

Stock Status: Estimated total stock biomass (males and female at age-1+) declines at the beginning of the time series until 2000, after which biomass becomes relatively stable (Fig. ES3A). Estimated female SSB exhibits a similar population trend, with an initial decline until 2003 followed by fluctuations without a clear trend through 2015 (Fig. ES3B). The estimated SPR (spawners per recruit relative to the unfished population) in 2015 is 0.53, which corresponds to a moderate exploitation intensity (i.e., 1-SPR = 0.47). Instantaneous fishing mortality at age (F-at-age) is similar in both sexes through age-5, peaking at age-4 and declining to a low at age-6, after which males experience higher F-at-age than females up to age 13 (Fig. ES4). Juvenile albacore aged 2 to 4 years comprised, on average, 70% of the annual catch between 1993 and 2015 (Fig. ES5) as reflected by the larger impact of the surface fisheries (primarily troll, pole-and-line) which remove juvenile fish, relative to longline fisheries, which primarily remove adult fish (Fig. ES6).

The Western and Central Pacific Fisheries Commission (WCPFC) adopted a limit reference point (LRP) for the spawning stock biomass of 20% of the spawning stock biomass when F=0 (20%$SSB_{current, F=0}$) (https://www.wcpfc.int/harvest-strategy). The 20%$SSB_{current, F=0}$ LRP is based on dynamic biomass and fluctuates depending on changes in recruitment. However, there are no adopted F-based limit reference points.

Stock status is depicted in relation to the limit reference point (LRP; 20%$SSB_{current, F=0}$) for the stock and the equivalent fishing intensity ($F_{20\%}$; calculated as 1-$SPR_{20\%}$) (Fig. ES7A). Fishing intensity (F, calculated as 1-SPR) is a measure of fishing mortality expressed as the decline in the proportion of the spawning biomass produced by each recruit relative to the unfished state. For example, a fishing intensity of 0.8 will result in a SSB of approximately 20% of SSB_0 over the long run. Fishing intensity is considered a proxy of fishing mortality.

The Kobe plot shows that the estimated female SSB has never fallen below the LRP since 1993, albeit with large uncertainty in the terminal year (2015) estimates. Even when alternative hypotheses about key model uncertainties such as natural mortality and growth were evaluated,

the point estimate of female SSB in 2015 (SSB_{2015}) did not fall below the LRP, although the risk increases with these more extreme assumptions (Fig. ES7B). The SSB_{2015} was estimated to be 80,618 t and was 2.47 times greater than the LRP threshold of 32,614 t (Table ES1). Current fishing intensity, $F_{2012-2014}$ (calculated as 1- $SPR_{2012-2014}$), was lower than potential F-based reference points identified for the north Pacific albacore stock, except $F_{50\%}$ (calculated as 1-$SPR_{50\%}$) (Table ES1).

Based on these findings, the following information on the status of the north Pacific albacore stock is provided:

1. The stock is likely not overfished relative to the limit reference point adopted by the Western and Central Pacific Fisheries Commission (20%SSB $_{current\ F=0}$), and

2. No F-based reference points have been adopted to evaluate overfishing. Stock status was evaluated against seven potential reference points. Current fishing intensity ($F_{2012-2014}$) is below six of the seven reference points (see ratios in Table ES1), except $F_{50\%}$.

Biological Reference Points: Biological reference points were computed with the base case model (Table ES1). It should be noted that the 20%$SSB_{current,\ F=0}$ LRP is based on dynamic biomass and fluctuates depending on changes in recruitment (Fig. ES3B). In addition, all F-based reference points were calculated as the fishing intensity (1-SPR) equivalents of the reference points. The point estimate of maximum sustainable yield (MSY; includes male and female of all age classes removed by fisheries) was 132,072 t and the point estimate of female SSB to produce MSY (SSB_{MSY}) was 24,770 t. The ratio of $F_{2012-2014}/F_{MSY}$ was estimated to be 0.61 and the ratio of $SSB_{2015}/20\%SSB_{current,\ F=0}$ was estimated to be 2.47. Current fishing intensity ($F_{2012-2014}$) is below F_{MSY} and all MSY-proxy reference points except $F_{50\%}$, and SSB_{2015} is well above the LRP threshold (Table ES1).

Future Projections: Two 10-yr projection scenarios, constant $F_{2012-2014}$ and constant catch (average of 2010-2014 = 82,432 t) were conducted externally to the base case model to evaluate impacts on future female SSB. Future recruitment was based on the expected recruitment variability (σ_R = 0.5) and estimated autocorrelation (R = -0.13) of the recruitment time series (1993 – 2015) in the base case model. The overall sex-specific F-at-age was estimated from the base case model and used (scaled to the appropriate catch in the constant catch scenario) to remove albacore from the appropriate age and sex in the projected populations. There were two main sources of uncertainty in the projections: 1) uncertainty in the total biomass estimates; and 2) uncertainty in the future recruitment. Projections started in 2015 and continued for 10 years through 2025.

The projections show that the current fishing intensity ($F_{2012-2014}$) is expected to reduce female SSB to 63,483 t (CI: 36,046 - 90,921 t) by 2025, with a 0.2 and <0.01 % probability of being below the LRP by 2020 and 2025, respectively (Fig. ES8). Median catch is expected to increase in 2017 and 2018 and then decline to about 60,000 t in 2024 when fishing at $F_{2012-2014}$ (Fig. ES8). However, median future catch is expected to be below the average catch level for 2010-2014 (82,432 t – red line in Fig. ES8). This result is most likely due to low estimated recruitment in 2011, which is expected to reduce female SSB beginning in 2015, the first year of the projection period. In contrast, employing the constant catch harvest scenario is expected to reduce female spawning biomass to 47,591 t (CI: 5,223 - 89,958 t) by 2025 and increases the probability that female SSB will be below the LRP to about 3.5 and 30 % in 2020 and 2025, respectively (Fig. ES9). The probabilities of female SSB falling below the LRP may be higher than estimated here because the future projections software does not incorporate all the estimated uncertainty from the base case model into the projections. It should be noted that the constant catch scenario is inconsistent with current management approaches for north Pacific albacore tuna adopted by the Inter-American Tropical Tuna Commission (IATTC) and the WCPFC.

Conservation Information: Two harvest scenarios were projected to evaluate impacts on future female SSB: F at the 2012-2014 rate over 10 years ($F_{2012\text{-}2014}$) and constant catch[1] (average of 2010-2014 = 82,432 t) over 10 years. Median female SSB is expected to decline to 63,483 t (95% CI: 36,046 - 90,921 t) by 2025, with a 0.2 and <0.01% probability of being below the LRP by 2020 and 2025, respectively, if fishing intensity remains at the 2012-2014 level[2] (Fig. ES8). In contrast, employing the constant catch harvest scenario is expected to reduce female SSB to 47,591 t (95% CI: 5,223 - 89,958 t) by 2025 and increases the probability that female SSB will be below the LRP to about 3.5 and 30% in 2020 and 2025, respectively (Fig. ES9). In addition, as biomass declines during the projection period the fishing intensity approximately doubles by 2025. Although the probabilities of declining below the LRP in both harvest scenarios are likely higher in the future, even the most extreme results from other model runs with plausible alternative assumptions show that female SSB is not likely to have declined below the LRP throughout the assessment period (1993 – 2015).

Based on these findings, the following information is provided:

1. If a constant fishing intensity ($F_{2012\text{-}2014}$) is applied to the stock, then median female spawning biomass is expected to decline and there will be < 0.01% probability of falling below the limit reference point established by the WCPFC by 2025. However, expected catches will be below the recent average catch level for this stock[2].
2. If a constant average catch ($C_{2010\text{-}2014}$ = 82,432 t) is removed from the stock in the future, then the decline in median female spawning biomass will be greater than in the constant F scenario and the probability that SSB falls below the LRP will be greater by 2025 (30%). Additionally, the estimated fishing intensity will double relative to the current level ($F_{2012\text{-}2014}$) by 2025 as spawning biomass declines.

Key Uncertainties: The ALBWG notes that the lack of sex-specific size data, uncertainty in growth and natural mortality, and the simplified treatment of the spatial structure of north Pacific albacore population dynamics are important sources of uncertainty in the assessment.

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[1] It should be noted that the constant catch scenario is inconsistent with current management approaches for north Pacific albacore tuna adopted by the Inter-American Tropical Tuna Commission (IATTC) and the WCPFC.

[2] Median future catch for the constant F scenario is expected to be below the average catch level for 2010-2014 (82,432 t – red line in Fig. ES8). This result is most likely due to low estimated recruitment in 2011, which is expected to reduce female SSB beginning in 2015, the first year of the projection period.

Table ES1. Estimates of maximum sustainable yield (MSY), female spawning biomass (SSB) quantities, and fishing intensity (F) based reference point ratios for north Pacific albacore tuna for the base case assessment and important sensitivity analyses. SSB_0 and SSB_{MSY} are the unfished biomass of mature female fish and at MSY, respectively. The Fs in this table are not based on instantaneous fishing mortality. Instead, the Fs are indicators of fishing intensity based on SPR and calculated as 1-SPR so that the Fs reflects changes in fishing mortality. SPR is the equilibrium SSB per recruit that would result from the current year's pattern and intensity of fishing mortality. Current fishing intensity is based on the average fishing intensity during 2012-2014 ($F_{2012\text{-}2014}$).

Quantity	Base Case	M = 0.3 y^{-1}	Growth CV = 0.06 for L_{inf}
MSY (t) [A]	132,072	92,027	118,836
SSB_{MSY} (t) [B]	24,770	42,098	22,351
SSB_0 (t) [B]	171,869	270,879	156,336
SSB_{2015} (t) [B]	80,618	68,169	63,719
$SSB_{2015}/20\%SSB_{current, F=0}$ [B]	2.47	1.31	2.15
$F_{2012\text{-}2014}$	0.51	0.74	0.57
$F_{2012\text{-}2014}/F_{MSY}$	0.61	0.89	0.68
$F_{2012\text{-}2014}/F_{0.1}$	0.58	0.90	0.65
$F_{2012\text{-}2014}/F_{10\%}$	0.56	0.81	0.63
$F_{2012\text{-}2014}/F_{20\%}$	0.63	0.91	0.71
$F_{2012\text{-}2014}/F_{30\%}$	0.72	1.04	0.81
$F_{2012\text{-}2014}/F_{40\%}$	0.85	1.21	0.96
$F_{2012\text{-}2014}/F_{50\%}$	1.01	1.47	1.16

A – MSY includes male and female juvenile and adult fish
B – Spawning stock biomass (SSB) in this assessment refers to mature female biomass only.

Figure ES1. Estimated total annual catch of north Pacific albacore (*Thunnus alalunga*) by all countries harvesting the stock, 1993-2015. ISC member country catches and catches by Vanuatu, which might include small catches by other countries such as Tonga, Belize, Cook Islands, and Marshall Islands.
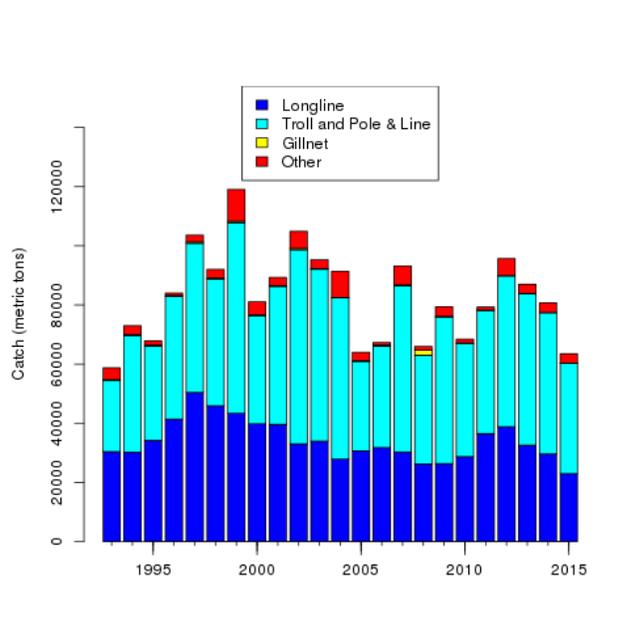
Figure ES2. Estimated catches of north Pacific albacore (*Thunnus alalunga*) by major gear types, 1993-2015. The Other gear category includes catches with purse seine, recreational gear, hand lines, and harpoons.

A.

B.

C.
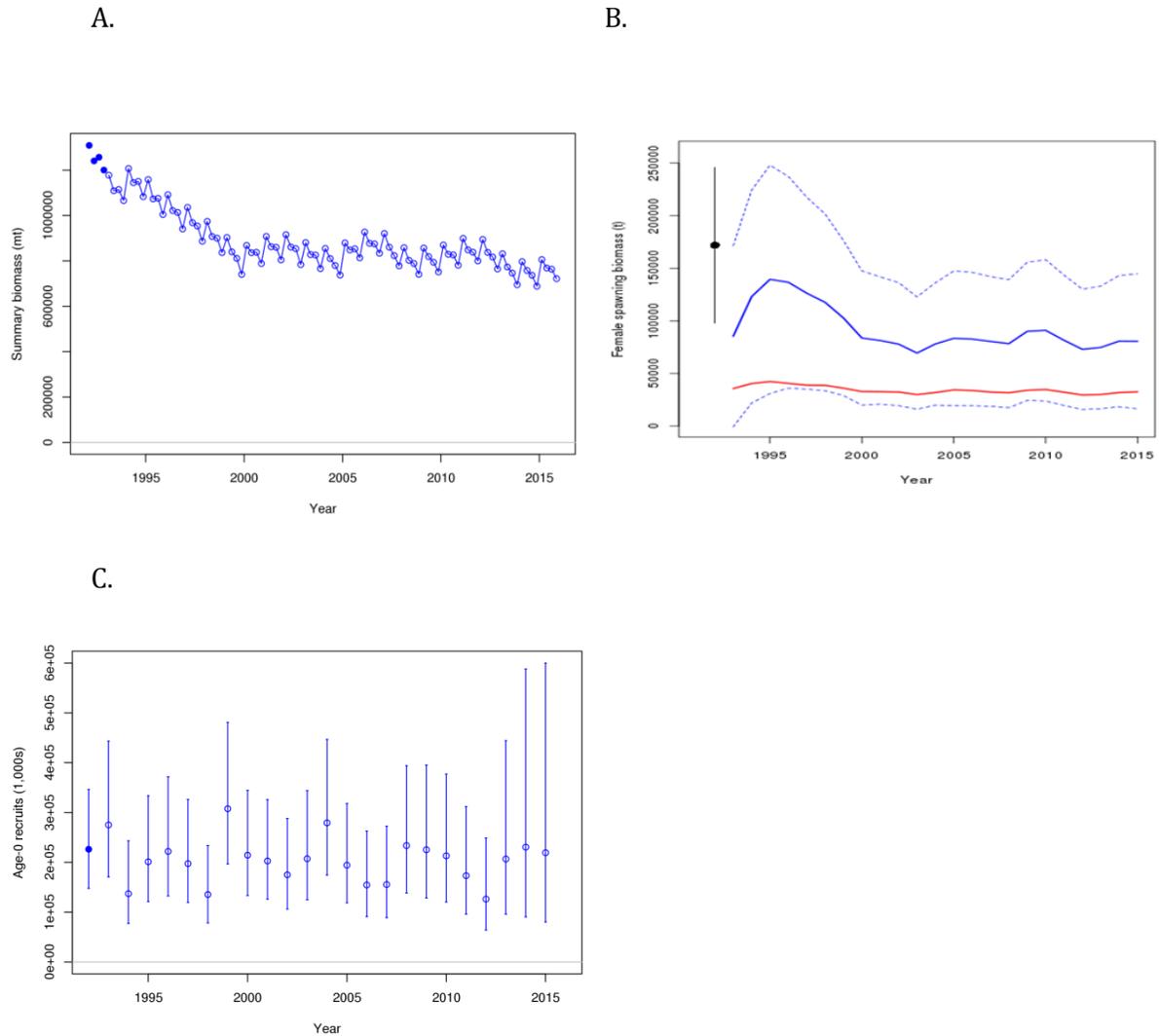
Figure ES3. Maximum likelihood estimates of (A) total age-1+ biomass (open circles) (B), female spawning biomass (SSB) (solid blue line), and (C) age-0 recruitment (open circles) of north Pacific albacore tuna (*Thunnus alalunga*). Dashed lines (B) and vertical bars (C) indicate 95% confidence intervals of the female SSB and recruitment estimates respectively. Red line indicates the 20%$SSB_{current, F=0}$ limit reference point, which is based on dynamic SSB_0. Closed black circle and error bars in (B) are the maximum likelihood estimate and 95% confidence intervals of unfished female spawning biomass, SSB_0. Since the assessment model represents time on a quarterly basis, there are four estimates of total biomass (A) for each year, but only one annual estimate of female SSB (B) and recruitment (C).

Figure ES4. Estimated sex-specific instantaneous fishing mortality-at-age (F-at-age) for the 2017 base case model, averaged across 2012-2014.
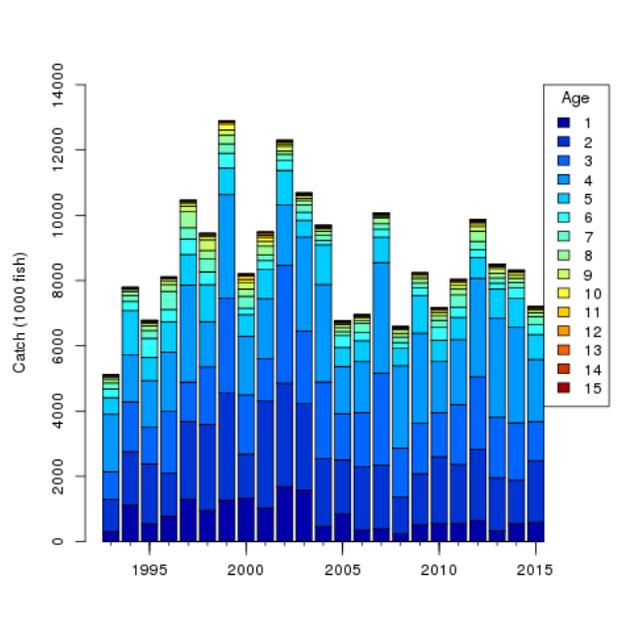
Figure ES5. Historical catch-at-age of north Pacific albacore (*Thunnus alalunga*) estimated by the 2017 base case model.
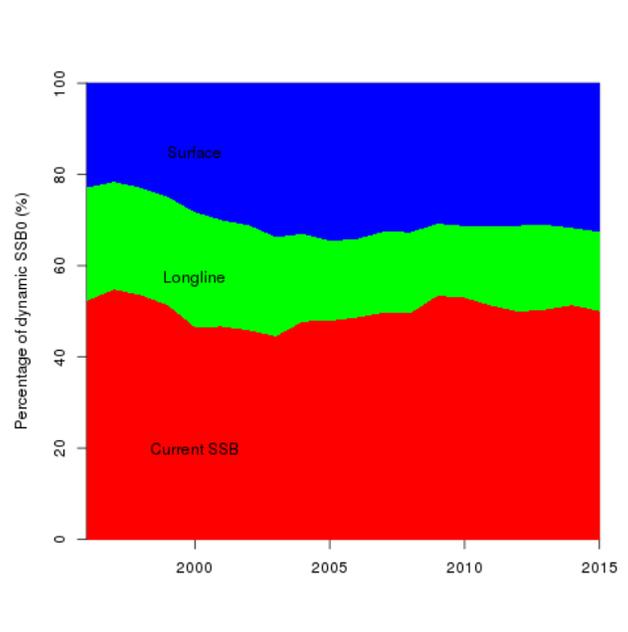
Figure ES6. Fishery impact analysis on north Pacific albacore (*Thunnus alalunga*) showing female spawning biomass (SSB) (red) estimated by the 2017 base case model as a percentage of dynamic unfished female SSB (SSB_0). Colored areas show the relative proportion of fishing impact attributed to longline (USA, Japan, Chinese-Taipei, Korea and others) (green) and surface (USA, Canada, and Japan) (blue) fisheries (primarily troll and pole-and-line gear, but including all other gears except longline).
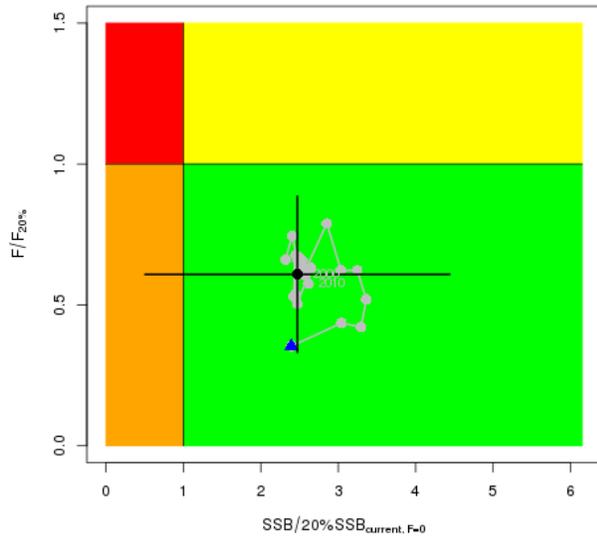
A   **B**
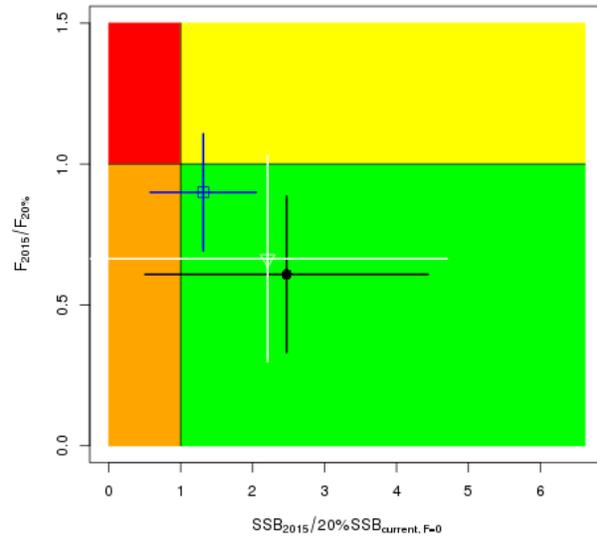
Figure ES7. (**A**) Kobe plot showing the status of the north Pacific albacore (*Thunnus alalunga*) stock relative to the $20\%SSB_{current,\ F=0}$ biomass-based limit reference point, and equivalent fishing intensity ($F_{20\%}$; calculated as $1-SPR_{20\%}$) over the base case modeling period (1993-2015). Blue triangle indicates the start year (1993) and black circle with 95% confidence intervals indicates the terminal year (2015). (**B**) Kobe plot showing stock status and 95% confidence intervals in the terminal year (2015) of the base case model (black; closed circle) and important sensitivity runs with $M = 0.3\ y^{-1}$ for both sexes (blue; open square), and $CV = 0.06$ for L_{inf} in the growth model (white; open triangle). Fs in this figure are not based on instantaneous fishing mortality. Instead, the Fs are indicators of fishing intensity based on SPR and calculated as 1-SPR so that the Fs reflects changes in fishing mortality. SPR is the equilibrium SSB per recruit that would result from the current year's pattern and intensity of fishing mortality.

Figure ES8. (A) Historical and future trajectory of north Pacific albacore (*Thunnus alalunga*) female spawning biomass (SSB) under a constant fishing intensity ($F_{2012-2014}$) harvest scenario. Future recruitment was based on the expected recruitment variability and autocorrelation. Black line and blue area indicates maximum likelihood estimates and 95% confidence intervals (CI), respectively, of historical female SSB, which includes parameter uncertainty. Red line and red area indicates mean value and 95% CI of projected female SSB, which only includes future recruitment variability and SSB uncertainty in the terminal year. (B) Expected annual catch under a constant fishing intensity ($F_{2012-2014}$) harvest scenario (2016-2025). The red line is the current average catch (2010-2014 = 82,432 t).

Figure ES9. (A) Historical and future trajectory of north Pacific albacore (*Thunnus alalunga*) female spawning biomass (SSB) under a constant catch (average 2010-2014 = 82,432 t) harvest scenario. Future recruitment was based on the expected recruitment variability and autocorrelation. Dashed line indictaes the average limit reference point threshold for 2012-2014. Black line and blue area indicates maximum likelihood estimates and 95% confidence intervals (CI), respectively, of historical female SSB, which includes parameter uncertainty. Red line and red area indicates mean value and 95% CI of projected female SSB, which only includes future recruitment variability and SSB uncertainty in the terminal year. (B) Projected fishing intensity relative to the current fishing inetnsity (2012-2014) (red line) under a constant catch scenario (average 2010-2014).

1.0 INTRODUCTION

The Albacore Working Group (ALBWG) of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC) is tasked with conducting regular stock assessments of north Pacific albacore tuna (*Thunnus alalunga*) to estimate population parameters, summarize stock status, and develop scientific advice on conservation needs for fisheries managers. The origins of the ALBWG date to 2005 when the *North Pacific Albacore Workshop*, which was established in 1974 to promote cooperative research and stock assessment analyses on north Pacific albacore, was integrated into the ISC. The ALBWG consists of members from coastal states and fishing entities of the region (Canada, China, Chinese-Taipei, Japan, Korea, Mexico, USA) and members from relevant intergovernmental fishery and marine science organizations (e.g., Inter-American Tropical Tuna Commission, Secretariat of the Pacific Community).

The previous stock assessment in 2014 used an integrated, length-based, and age- and sex-structured forward-simulating statistical stock assessment model in the Stock Synthesis (SS) modeling framework (Methot and Wetzel 2013) to assess stock status. The 2014 model included a new sex-specific growth model considered to be more representative of growth in the stock (Xu et al. 2014), whose parameters were based on conditional age-at-length data published by Chen et al. (2012) and Wells et al. (2013). Although biomass scale was uncertain, female spawning stock biomass (SSB) in the terminal year of the assessment (2012) was estimated to be 35.8% of unfished SSB and exploitation level of the stock was relatively low (i.e., 1-SPR = 0.59). Based on an evaluation of $F_{2010-2012}$ against a variety of F-based reference points, the ALBWG concluded in 2014 that the stock was not experiencing overfishing. Although there were no biomass-based reference points developed for the stock in 2014, the ALBWG concluded that the stock was not likely in an overfished condition because there was little evidence that fishing had reduced SSB below reasonable candidate biomass-based reference points.

Since the last assessment in 2014, several developments in the science and management of north Pacific albacore tuna have strongly influenced the development of this stock assessment. Most importantly, the Northern Committee (NC) of the Western and Central Pacific Fisheries Commission (WCPFC), which manages this stock together with the Inter American Tropical Tuna Commission (IATTC), adopted a biomass-based limit reference point (LRP) of $20\%SSB_{current, F=0}$ (WCPFC 2014). The adoption of this LRP emphasized the importance of estimating population scale from the assessment model. However, an analysis of the 2014 assessment model showed that population scale may not have been well estimated because changes in the adult abundance indices were not reflective of changes in the catch, that is, the 2014 indices lacked a production function (Minte-Vera and Maunder 2016).

The ALBWG made three major improvements to the 2017 assessment model compared to previous assessment models. First, and most importantly, an improved adult albacore index (1996 – 2015) was developed from Japanese longline fishery logbook data using Generalized Linear Mixed Models (GLMMs) (Ochi et al. 2017). Second, the assessment model had a start year of 1993 instead of 1966 because of uncertainty in the representativeness of size composition data from Japanese longline vessels in the 1980s and early 1990s, and potential differences in growth between these periods. Third, age and sex-specific natural mortality parameters derived from meta-analyses were used rather than assuming constant natural mortality for all ages and sexes as in previous assessments (see Section 2.3 for more details).

This report presents the results of the 2017 assessment of north Pacific albacore tuna and scientific advice on stock status and conservation needs to fisheries managers. The assessment uses updated fishery data through 2015 in a length-based, age- and sex-structured integrated statistical stock assessment model fitted to an abundance index from the Japanese longline fisheries, which was considered to be representative of adult albacore abundance in the north Pacific Ocean. The assessment was conducted 11 – 19 April 2017 at the Southwest Fisheries Science Center in La Jolla, California, USA, and supersedes the 2014 assessment (ALBWG 2014). The objectives of this assessment are to: 1) understand the dynamics of the north Pacific albacore tuna stock by estimating population parameters such as time series of recruitment, biomass and fishing mortality; 2) determine stock status by summarizing results relative to a suite of biological reference points, including the $20\%SSB_{current, F=0}$ LRP and MSY-based reference points; and 3) to provide scientific advice on conservation needs for fisheries managers based on projections using constant fishing mortality and constant catch scenarios.

2.0 BACKGROUND

2.1 Biology

2.1.1 Stock structure

Albacore tuna in the Pacific Ocean consist of the north Pacific stock (focus of this assessment) and the south Pacific stock. The discreteness of these stocks is supported by fishery data [lower catch rates in equatorial regions; Suzuki et al. (1977)], tagging data [there are no south Pacific Ocean recoveries of fish tagged in the north Pacific Ocean; Ramon and Bailey (1996)], ecological data [albacore larvae are rare in samples from equatorial waters; Ueyanagi (1969)], and genetic data [showing differentiation between north and south Pacific albacore; Takagi et al. (2001)]. Thus, north Pacific albacore is assumed to be a discrete, reproductively isolated stock, with no internal sub-group structure within the stock.

2.1.2 Reproduction

Albacore are batch spawners, shedding hydrated oocytes, in separate spawning events, directly into the sea where fertilization occurs. Spawning frequency is estimated to be 1.7 d in the western Pacific Ocean (Chen et al. 2010), and batch fecundity ranges between 0.17 and 2.6 million eggs (Ueyanagi 1957, Otsu and Uchida 1959, Chen et al. 2010). Female albacore mature at lengths ranging from 83 cm fork length (FL) in the western Pacific Ocean (Chen et al. 2010) to 90 cm FL in the central Pacific Ocean (Ueyanagi 1957), and 93 cm FL north of Hawaii (Otsu and Uchida 1959).

Spawning occurs in tropical and sub-tropical waters between Hawaii (155°W) and the east coast of Taiwan and the Philippines (120°E) and between 10 and 25°N latitudes at depths exceeding 90 m (Ueyanagi 1957, 1969, Otsu and Uchida 1959, Yoshida 1966, Chen et al. 2010). Although spawning probably occurs over an extended period from March through September in the western and central Pacific Oceans, recent evidence based on a histological assessments of gonadal status and maturity (Chen et al. 2010) shows that spawning peaks in the March-April period in the western Pacific Ocean, which is consistent with evidence from larval sampling surveys in the same region (Nishikawa et al. 1985). In contrast, studies of albacore reproductive biology in the central Pacific Ocean have concluded that there was a probable peak spawning period between June and August (Ueyanagi 1957, Otsu and Uchida 1959), but these studies are based on indirect observation methods, are more than 50 years old, and have not been updated using modern histological techniques (e.g., see Chen et al. 2010).

2.1.3 Growth

Growth of albacore tuna is commonly modeled by a von Bertalanffy growth function, with rapid growth in immature fish followed by a slowing of growth rates at maturity and through the adult period. Growth in the first year of life is uncertain since these young fish are rarely captured in any of the active fisheries in the north Pacific Ocean. However, juvenile albacore recruit into intensive surface fisheries in both the eastern and western Pacific Oceans at age-2 and as a result, much better size-at-age and growth information is available. Early growth models combined both sexes because sex-specific fishery data were not collected, although it was known that adult males attained a larger size than females (Otsu and Uchida 1959, Yoshida 1966, Otsu and Sumida 1968). Chen et al. (2012) provided clear evidence of sexually dimorphic growth functions for males and females after they reach sexual maturity and reported that males attained a larger size and older age than females (114 cm FL and 14 years vs. 103.5 cm FL and 10 years, respectively).

A re-examination of the age and growth data compiled by Wells et al. (2013), some of which were used as conditional age-at-length data in the 2011 assessment, showed that for those individuals in which sex was recorded, there was clear evidence of sexually dimorphic growth between males and females (Xu et al. 2014). Given the clear evidence of sexual dimorphism in the growth and longevity of north Pacific albacore, the ALBWG used the same sex-specific male and female von Bertalanffy growth functions in this assessment as used in the 2014 assessment. These growth parameters were estimated externally to the stock assessment model by Xu et al. (2014), who combined the sex-specific datasets compiled by Chen et al. (2012) and Wells et al. (2013).

2.1.4 Movements

North Pacific albacore are highly migratory and these movements are influenced by oceanic conditions (e.g., Polovina et al. 2001, Zainuddin et al. 2006, 2008). The majority of the migrating population is believed to be composed of juvenile fish (i.e., immature animals that are less than 5 years old and 85 cm FL), which generally inhabit surface waters (0-50 m) in the Pacific Ocean. Some juvenile albacore undertake trans-Pacific movements from west to the east and display seasonal movements between the eastern or western and central Pacific Ocean (Ichinokawa et al. 2008, Childers et al. 2011). The trans-Pacific movements track the position of the transition zone chlorophyll front (Polovina et al. 2001, Zainuddin et al. 2006, 2008) and increase when large meanders in the Kuroshio current occur, increasing albacore prey availability in the transition zone (Kimura et al. 1997, Watanabe et al. 2004). Westward movements of juveniles tend to be more frequent than eastward movements (Ichinokawa et al. 2008), corresponding to the recruitment of juvenile fish into fisheries in the western and eastern Pacific Ocean and are followed by a gradual movement of older juveniles and mature fish to low latitude spawning grounds in the western and central Pacific Ocean. This pattern may be complicated by sex-related movements of large adult fish, which may be predominately male, to areas south of 20°N. The significance of sex-related movements on the population dynamics of this stock is uncertain at present.

2.2 Fisheries

Albacore tuna is a valuable species with a long history of exploitation in the north Pacific Ocean (e.g., Clemens 1961). The total reported catch of north Pacific albacore for all nations combined (Figure 2.1) peaked at a 126,175 metric tonnes (t) in 1976 and then declined to a lowest observed catch in the time series (37,274 t) in 1991. Following this low point, total catch recovered to a second peak of 119,297 t by 1999. Total catch declined through the 2000s to a low of 63,654 t in 2005 and has recovered slightly, fluctuating between 69,000 and 93,000 t in recent years (2010-2015). Average catch over the model time frame (1993-2015) is 82,724 t. Over the last five years

(2011-2015), Japanese fisheries accounted for 61.9% of the annual total harvest on average, followed by fisheries from the United States (16.9%), Canada (5.4%), China (4.3%), Chinese-Taipei (3.9%), Korea (0.1%), and Mexico (<0.1%). During the same five year period, non-ISC countries, primarily Vanuatu, harvested an average of 7.3% of the total annual catch.

The main gears deployed to harvest albacore in the north Pacific Ocean are longline, and troll and pole-and-line (Fig. 2.2). Surface fisheries capture smaller, juvenile fish, and include the USA and Canada troll and pole-and-line fisheries and Japanese pole-and-line fisheries. Over the model time frame (1993 – 2015), surface fisheries have harvested approximately 53.6 % of the north Pacific albacore catch. Longline fisheries, which fish deeper in the water column and tend to capture larger, mature albacore, were responsible for harvesting about 41.7 % of the albacore during the same period, with major fleets from Japan, USA, Chinese-Taipei, and recently China and Vanuatu. Pole-and-line catches in the 2000s exhibited greater year-to-year variability than catches by the other gear types since they are influenced by target switching between skipjack (*Katsuwonus pelamis*) and albacore by some vessels on the fishing grounds off the east coast of Japan (Kiyofuji and Uosaki 2010). High gillnet catches of albacore in the 1980s reflect data from high seas driftnet fisheries, which began in 1978 and ceased operating in 1993 as a result of United Nations General Assembly Resolution 44/225, which put in place a moratorium on the use of high seas driftnets (Uosaki et al. 2011).

2.3 Important Changes from 2014 Assessment

2.3.1 Abundance indices

The 2014 base case model was fitted to two Japanese longline indices representing two periods of adult albacore abundance trends (1975-1992; 1993-2012). In addition, two Japanese pole-and-line indices were used to represent the juvenile albacore abundance trends over two periods (1972-1989; 1990-2012). However, in this assessment, the base case model had a start year of 1993 (see Section 2.3.2) and was only fitted to one Japanese longline index (1996 – 2015) representing the adult albacore abundance trend.

An age-structured production model (ASPM) diagnostic analysis of the 2014 assessment model showed that changes in the adult abundance indices were not reflective of changes in the catch (Minte-Vera and Maunder 2016). The ASPM diagnostic was proposed by Maunder and Piner (2015) as an indicator of the presence of a production function for indices in an integrated assessment model. If an ASPM, modified from the assessment model, is able to fit the abundance indices with good contrast, then this finding is considered evidence that the indices will likely be able to provide information on the scale of the population. The ASPM diagnostic showed that the indices used in the 2014 assessment did not exhibit a production function, i.e., a relationship between the index and catch-at-age data. Although the size composition data did not have a disproportionally large effect on the 2014 assessment results due to the use of heavy down-weighting on these size composition data, there was a conflict between the indices and size composition data in the 1975 – 1992 period (Minte-Vera and Maunder 2016). Given the adoption by the NC of of the 20%$SSB_{current, F=0}$ as a biomass-based LRP more certainty in the estimated scale of the population is an important attribute of the 2017 assessment.

The most important improvement in the 2017 assessment was the development of an improved adult albacore index (1996 – 2015) from Japanese longline fishery logbook data using Generalized Linear Mixed Models (GLMMs) (Ochi et al. 2017). This new index had good contrast and preliminary ASPM analysis showed that an ASPM was able to fit well to the index, which is evidence that the new index is informative on both population trend and scale (ALBWG 2017). This

improvement was primarily due to an improvement in the fishery definitions used in this assessment (Section 3.3) and a new standardization model applied to the data (Section 3.5). The ALBWG therefore focused on fitting the model to this index and reducing conflicts among the data to this index.

Preliminary model runs indicated that the Japanese pole-and-line indices were not well-fitted and had conflicts with the other data in the model, including the Japanese longline index. In addition, the size composition data of the Japanese pole-and-line fleets were highly variable, with different age classes being sampled by season and year. This suggest that the selectivities and likely catchabilities of the Japanese pole-and-line fleets were highly variable or that the size compositions were not representative of the catch. The ALBWG therefore decided to not fit to the Japanese pole-and-line indices and rely primarily on the Japanese longline index.

2.3.2 Modeling period

Changing the start year from 1966 in the 2014 assessment to 1993 is considered an additional improvement in the 2017 assessment. This change was made to eliminate the effect of poorly fit size compositions from the Japanese longline fisheries in the 1975 – 1992 period on model results, and to eliminate the conflict between these size composition data and the primary longline indices in the 1975-1992 period highlighted by the results of an ASPM analysis of the 2014 assessment model (Minte-Vera and Maunder 2016).

A large proportion of size samples from Japanese longline vessels during the 1980s and early 1990s consisted of large fish (≥100 cm FL) and were poorly fitted in preliminary models with reasonable selectivity processes. Size composition data from Japanese longline fisheries during the 1980s and 1990s were mostly from a single port (Yaizu port in Shizuoka prefecture) and it is currently unclear whether these samples were representative of the entire catch from the Japanese longline fisheries. The vast majority (>90%) of these albacore size samples came from vessels fishing in areas <30°N during the 1980s and early 1990s. This suggests that growth, especially the L_{inf} parameter, might have been different during the 1980s and early 1990s than in other periods. Alternatively, the Japanese longline vessels might have been mostly operating in areas primarily inhabited by very large albacore during that period but no longer operate in those areas in subsequent periods. However, the ALBWG has no evidence that the operational areas for these vessels have changed substantially before or after the 1980s-early 1990s period. Given the uncertainty in the representativeness of the size composition data from Japanese longline vessels in the 1980s and early 1990s, and the potential differences in growth between periods, the ALBWG decided to start the model from 1993 instead of 1966. Starting the model from 1993 allowed the ALBWG to estimate population scale from the new adult albacore index, which was shown to be informative on population scale. In addition, starting the model in 1993 allowed the ALBWG to avoid modelling potentially unrepresentative size composition data from the 1980s and early 1990s that may be misinformative on population scale.

2.3.3 Natural mortality

Another major improvement in this assessment is the use of age and sex-specific natural mortality parameters. In previous assessments, the instantaneous rate of natural mortality (M) was assumed to be 0.3 y^{-1} for both sexes at all ages. The ALBWG reviewed the basis for this assumption and found that this assumption was not well supported in the scientific literature (Kinney and Teo 2016). Furthermore, an analysis by ICCAT (2011) suggested that M should instead be 0.420 or 0.456 y^{-1} (Kinney and Teo 2016).

For the 2017 assessment, the ALBWG incorporated results from studies that used meta-analytical methods on a range of empirical relationships between M and life history parameters (Hamel 2015, Then et al. 2015, Kinney and Teo 2016, Teo 2017a). These analyses identified an M of 0.38 and 0.49 y^{-1} for adult males and female albacore tuna, respectively. These results corresponded well to an independent study of tagging data, which estimated a non sex-specific M of 0.45 – 0.5 for north Pacific albacore (Ichinokawa et al. 2008). Based on these results for adult albacore, the ALBWG assumed that the M of juvenile north Pacific albacore tuna followed a Lorenzen (1996) function from age-0 to age-2, which scales M based on size with no difference between the sexes until age-3+. Upon reaching age-3, the M for male albacore is assumed to be 0.38 y^{-1} and the M for female albacore is assumed to be higher, at 0.49 y^{-1}, which may reflect the cost of reproduction. This age and sex-specific M schedule is an improvement over the previous assumption of a constant M for all ages and sexes because it is based on an analysis of currently available scientific information. However, it should be noted that the higher adult Ms are consistent with a north Pacific albacore stock that is more productive than previously assumed.

3.0 DATA

Three types of data were used in this assessment: fishery-specific catches, size composition, and abundance indices. These data were originally compiled from 1966 through 2015, but the ALBWG subsequently decided to start the model in 1993 (Section 2.3.2). Therefore, only data from 1993 – 2015 are shown in this report. Data sources and temporal coverage of the available datasets are summarized in Figure 3.1.

3.1 Spatial Stratification

The geographic area of this assessment is the Pacific Ocean north of the equator (0°) to 55°N and from 120°E to 100°W (Fig. 3.2). This area includes all of the known catches of north Pacific albacore from 1993 through 2015. The base case model is not spatially explicit but fisheries were defined using multiple criteria, including fishing area, and therefore implicitly included spatial inferences (Table 3.1). Analyses of fishing operations and size composition data from Japanese and US longline vessels in the north Pacific showed that there were five areas with relatively consistent size distributions of albacore (ALBWG 2016, Ochi et al. 2016, Teo 2016) (Fig 3.2). These five fishing areas were used by the ALBWG to define fisheries in the base case model (Section 3.3).

3.2 Temporal Stratification

The time frame for the 2017 assessment was 1993–2015. Catch and size composition data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec) and a quarterly time step was used in the base case model. Although the catch data time series extended back to at least 1952 for some fisheries, the ALBWG decided to start the assessment model in 1993 instead of 1966 because of uncertainty in the representativeness of size composition data from Japanese longline vessels in the 1980s and early 1990s, and potential differences in growth between periods (Section 2.3.2). Nevertheless, sensitivity runs were conducted to evaluate the effect of different starting years on estimated quantities (Sections 4.7 and 5.6.4).

3.3 Fishery Definitions

Twenty-nine (29) fisheries were defined for the assessment on the basis of gear, fishing area, season, and unit of catch (numbers or weight), and all catch and effort data were allocated to these fisheries (Table 3.1). The aim was to define relatively homogeneous fisheries with greater

differences in selectivity and catchability between fisheries than temporal changes in these parameters within fisheries. This approach allowed the ALBWG to use differences in selectivity between fisheries as proxies for movement between fishing areas (Hurtado-Ferro et al. 2014, Waterhouse et al. 2014) since movement information is not available. These fisheries consisted primarily of 23 longline fisheries from Japan (F1 – F15), USA (F19 & F20), Chinese-Taipei (F21 & F22), Korea (F23), China (F24 & F25), and Vanuatu (F26) (Table 3.1). There were also three pole-and-line fisheries from Japan (F16 – F18), and the surface gears (primarily troll and pole-and-line) from Canada, Mexico, and the USA, which were combined into a single surface gear fishery (F27). In addition, drift net catches from Japan, Korea, and Chinese-Taipei were combined into a single fishery (F28), which was important in the past but less so during the modeling period; and catch from all other miscellaneous gears (e.g., purse-seine) from Japan and Chinese-Taipei were combined into a single miscellaneous fishery (F29). The approximate fishing area of each fishery can be deduced from Table 3.1 and Figure 3.2.

3.4 Catch

Estimates of total catch in each fishery (Table 3.1) were compiled by calendar quarter for 1966-2015 but only catch during 1993 – 2015 were used for the base case model (Fig. 3.3). Catch was reported and compiled in original units consisting of weight or 1000s of fish (Table 3.1).

3.5 Relative Abundance Indices

The ALBWG reviewed 13 abundance indices, including Japanese longline (Ochi et al. 2017), Japanese pole-and-line (Kinoshita et al. 2016, 2017), Taiwanese longline (Chen and Cheng 2016), USA longline (Teo 2017b), and USA surface (Teo 2017c) fisheries. Based on this review, the ALBWG decided to use the abundance index from the Japanese longline fishery in Area 2 and Quarter 1 (S1; 1996 - 2015) as the index of adult albacore abundance (Ochi et al. 2017). This index is an appropriate index for adult albacore in the north Pacific because the majority of the adult albacore population in the north Pacific Ocean is thought be in the western Pacific, especially Area 2. In addition, the S1 index had good contrast and preliminary ASPM analysis results showed that an ASPM was able to fit well to the index, which the ALBWG interpreted as an indication that the S1 index was informative on both population trend and scale.

Preliminary model runs found that the Japanese pole-and-line index was not well-fit and conflicted with the other data, including the Japanese longline index. In addition, the size composition data of the Japanese pole-and-line fleets were highly variable, with different age classes sampled by season and year. These results and observations are consistent with the idea that the selectivities and likely catchabilities of the Japanese pole-and-line fleets were highly variable or that the size compositions were not representative of the catch. The ALBWG therefore decided to not fit to the Japanese pole-and-line index in the base case model, but use this index in sensitivity runs. Other indices were not considered in this assessment based on experience in the 2011 and 2014 assessments.

Standardized annual values and input coefficients of variation (CVs) for the S1 index used in the base case model and Japanese pole-and-line index used in sensitivity runs are shown in Table 3.2 and Figure 3.4. Seasons were assigned to each index based on the quarter in which the majority of catch was recorded. The relative weighting of the indices was controlled by adjusting the input CVs (Section 4.4).

3.5.1 S1 – Japanese longline index (1996 – 2015)

The only index that was fitted in the base case model was developed by Ochi et al. (2017) using set-by-set catch (number of albacore) and effort (1000s of hooks) data from logbooks of Japanese longline vessels operating in Area 2 in Quarter 1 (identical to F9; Table 3.1) during 1996 – 2015. A Bayesian zero-inflated negative binomial generalized linear mixed effects model (Bayesian ZINB GLMM) was used to standardize the catch and effort data. Year, quarter, hooks-per-basket, and fleet-type (distant-water, offshore, coastal) were used as fixed explanatory factors while location (5°x5° strata) and vessel were used as random effects (Ochi et al. 2017). The ALBWG observed that the Pearson residuals in preliminary indices were biased in 1994 and 1995, and therefore decided to start the index in 1996. Ochi et al. (2017) had also developed indices for 1975 – 1992 but this index was not considered because the start year of the base case model was 1993. Further details on the data and standardization model can be found in Ochi et al. (2017).

3.5.2 Japanese pole-and-line index (1993 – 2015; sensitivity run)

The Japanese pole-and-line index in this assessment was very similar to the juvenile indices used in the 2014 assessment (ALBWG 2014). The most important difference was a change in the area (Area 3) and quarter (Quarter 3) definition to make the index consistent with F17 in the 2017 model (Kinoshita et al. 2016, 2017). The index was based only on data from the distant-water component of the pole-and-line fishery to minimize the influence of target switching between albacore and skipjack tuna in segments of the offshore pole-and-line fleet. The catch and effort data from 1990 – 2015 were standardized with a delta-lognormal model using year, quarter, and area (1°x1° strata) as explanatory variables. This index was only used in sensitivity model runs (Section 5.6.5). The start year of the model was changed to 1993 after the development of the index, so the index values for 1990–1992 were discarded instead of re-standardizing the index with a 1993–2015 data set. Although this approach may have resulted in a biased index, the ALBWG notes that this index was only used in sensitivity model runs and not base case runs used to generate scientific advice to managers.

3.6 Size Composition

Quarterly length composition data from 1993 through 2015 were used in this assessment. Length data were available for 19 of the 29 fisheries in the base case model (Table 3.1 and Fig. 3.5) and were compiled into 2-cm size bins, ranging from 26 to 142 cm FL, where the labels are the lower boundary of each bin. Most of these fisheries exhibited clear modes when lengths were aggregated across quarters and years (Fig. 3.5). The length data for the Japanese pole-and-line fisheries (F16 – F18) exhibited exceptionally high variability in the number of modes and mean sizes between seasons and years.

The length frequency observations were the estimated catch-at-size (i.e., size compositions were raised to the catch) for 15 of the fisheries with size composition data and these size composition data were fitted in the base case model (Table 3.1). However, the size composition data from four of the fisheries (F23 – F26) could not be raised to the catch and the base case model was not fitted to these data. Instead, it was assumed that the selectivity of these fisheries were the same as other longline fisheries with similar fishing operations and fishing area (Section 4.3.1).

The majority of albacore length composition data were collected through port sampling or on-board sampling by vessel crews or observers. Length data for the Japanese longline (F1 – F4; F9 – F10; F13; & F15) and pole-and-line fisheries (F16 – F18) were measured to the nearest cm at the landing ports or onboard fishing vessels from which catch-at-size data were derived (Ijima et al.

2017). Fork lengths of albacore in the EPO surface fishery (F27) were compiled from port samples of the USA troll and pole-and-line fisheries (Teo 2017d). Although length composition data were available for the Canadian component of this fishery (2008-present), these data were not used because the USA and Canada components of the fishery overlap greatly in their fishing areas and size composition plots of both fisheries are very similar so the data from the USA component were thus considered representative of the entire fishery. Length compositions for the US longline fishery were collected by observers (Teo 2017e). Albacore lengths for the Taiwanese longline fishery (F21) were measured onboard fishing vessels and compiled for 1995 to 2015 by the Overseas Fisheries Development Council (OFDC) of Chinese-Taipei (Chen and Cheng 2017). Length composition data prior to 2003 were not considered representative of catches by this fishery because they were sampled from a restricted geographic area and shorter annual time period than the spatial and temporal scope at which the fishery was operating (ALBWG 2014). Thus, only the 2003-2015 length data were considered representative of the catch and used in the base case model.

3.6 Sex Composition

Size composition data from Japanese longline training and research vessels are the primary source of sex ratio information for north Pacific albacore because sex composition data are not normally collected by commercial fisheries. Although sample sizes of sexed individuals only ranged from about 10 to 300 fish per year, the sex composition data show that males reach larger sizes than females (Figure 3.6), and that the sex ratio of males to females becomes heavily biased towards males at large sizes (>100 cm FL) (Ashida et al. 2016). This bias towards males at large sizes also has been observed in south Pacific albacore (Farley et al. 2013), and is likely due to the sex-specific differences in growth (Williams et al. 2012, Chen et al. 2012) and natural mortality (Kinney and Teo 2016). Although sex composition data from Japanese training and research vessels were available for this assessment, the data were submitted late and were not reviewed for the assessment. Therefore, the sex composition data were not fitted in the base case model but were instead used as a visual comparison with the expected sex ratio from the base case model.

4.0 MODEL DESCRIPTION

The 2017 stock assessment of north Pacific albacore tuna was conducted using the Stock Synthesis (SS) modeling platform (Methot 2000, Methot and Wetzel 2013). A sex-specific, length-based, age-structured, forward-simulating, fully-integrated, statistical model was developed for the stock assessment. The specification of the base case model for north Pacific albacore followed several steps. First, the spatial and temporal extent of fisheries in the assessment were defined based on analyses of the biology and historical fishing operations of albacore fisheries (ALBWG 2016). Second, the data sources and inputs for these fisheries in the model, including total catch, indices of relative abundance, and size compositions were identified, collated and reviewed for completeness, trends, and outliers or unusual behaviour. Third, important biological parameters (e.g., growth, stock-recruitment relationship) were obtained from previous studies after review by the ALBWG and included in the model as fixed parameters, or estimated within the assessment model (Table 4.1). Based on these inputs, preliminary models were developed and iteratively refined through an analysis of model fits (e.g., total and component negative log-likelihoods) and diagnostic outputs (e.g., ASPM, R_0 profiles, Pearson residuals), resulting in a base case model, with several differences from the base case model in the 2014 stock assessment (ALBWG 2014), including a shorter modeling period of 1993 – 2015, improved fisheries definitions and abundance indices, and a sex and age-specific natural mortality schedule (Section 2.3).

4.1 Stock Synthesis

Stock Synthesis is a highly flexible, statistical age-structured population modeling platform that can incorporate multiple data types and account for a variety of biological, fishery, and environmental processes (Methot and Wetzel 2013). Importantly for this assessment, SS can model sex-specific growth but fit to non-sex-specific observations. Although SS was initially developed and used in US domestic stock assessments, particularly groundfish assessments on the US west coast, its use has spread to stock assessments of large pelagic fish like tunas and sharks because of the flexibility it provides for modelling multiple data types and processes.

The SS platform consists of three subcomponents: 1) a population dynamics subcomponent that simulates the assessed population (i.e., population numbers and biomass at age) using processes such as natural and fishing mortality, and the stock-recruitment relationship; 2) an observational subcomponent that relates the modeled population dynamics to observed quantities including abundance indices and size composition data; and 3) a statistical subcomponent that quantifies the fit of the observations to the simulated population using maximum likelihood methods. The 2017 north Pacific albacore assessment model was implemented using SS version 3.24ab, which is available upon request from the ALBWG or NOAA (Methot 2000, Methot and Wetzel 2013).

4.2 Biological and Demographic Assumptions

4.2.1 Maximum age

The maximum age bin in the model was 15 years based on the maximum observed age (Wells et al. 2013). This bin served as the accumulator for all older ages. To avoid potential biases associated with the approximation of dynamics in the accumulator age, the maximum longevity was set at an age sufficient to result in near zero fish in this age bin ($\approx$ 1 percent of an unfished cohort).

4.2.2 Growth

The 2017 assessment used the same sex-specific growth curves as the base model for the previous assessment in 2014, which were based on the study by Xu et al (2014). Sex-specific growth curves were used because studies have found that north Pacific albacore tuna exhibit sex-specific growth, with male albacore exhibiting larger size at age after maturing and growing to larger size (Chen et al. 2012, Xu et al. 2014). Xu et al. (2014) combined age-at-length data from Chen et al. (2012), who primarily aged otolith samples from the northwestern Pacific, and Wells et al. (2013), who primarily obtained samples from the central and eastern North Pacific, to develop sex-specific growth curves covering the entire north Pacific Ocean.

A von Bertalanffy growth function, as parameterized by Schnute (1981), was used to model the relationship between fork length (cm) and age for north Pacific albacore:

$$L_2 = L_{inf} + (L_1 - L_{inf})e^{-K(A_2 - A_1)}$$

where L_1 and L_2 are the sizes associated with ages, A_1 and A_2, respectively, L_{inf} is the asymptotic length, and K is the growth coefficient.

In this assessment, L_1 was fixed at 43.504 and 47.563 cm for females and males at age 1, respectively (Table 4.1). The L_{inf} and K parameters were also fixed at sex-specific values from Xu et al. (2014) (L_{inf} - female: 106.570 cm, male: 119.150 cm; K - female: 0.2976 y^{-1}, male: 0.2077 y^{-1}) (Fig. 4.1). The coefficients of variation (CVs) of size-at-age at L_1 (CV$_1$) and L_{inf} (CV$_2$) were fixed at 0.06 and 0.04 for both female and male albacore in the base case model, based on estimates of these CVs

during preliminary runs. The CV_1 parameter was well estimated in the preliminary runs because of the clear modal structure in juvenile size composition data and the model results were not highly sensitive to this parameter. However, the CV_2 parameter was highly influential in the preliminary model results because of an interaction with the L_{inf} parameter. An analysis of conditional age-at-length data found that the variability of size-at-age for older albacore was similar to juvenile albacore and that the CV was approximately 0.04 (Xu et al. 2014). Sensitivity analyses of the CV_2 parameter and alternative growth models were performed (Table 4.1 and Section 5.6.3).

4.2.3 Weight-at-length

Non sex-specific weight-length relationships are used to convert catch-at-length to weight-at-length data (Fig. 4.2). A previous study (Watanabe et al. 2006) reported that there were seasonal differences in the relationship between weight (kg) and fork length (cm) of north Pacific albacore. These non sex-specific seasonal weight-at-length relationships were used in this assessment (Table 4.1) and the 2014 assessment (ALBWG 2014) because there were no previous studies documenting sex-specific differences in the weight-length relationships of north Pacific albacore.

4.2.4 Natural mortality

A major improvement in this assessment was the use of age and sex-specific natural mortality parameters from Teo (2017a) (Table 4.1). In previous assessments, M was assumed to be 0.3 y^{-1} for both sexes at all ages but this assumption was not well supported (Kinney and Teo 2016) (see Section 2.3.3). For this assessment, the ALBWG incorporated results from studies that used meta-analytical methods on a range of empirical relationships between M and life history parameters (Hamel 2015, Then et al. 2015, Kinney and Teo 2016, Teo 2017a), which identified an M of 0.38 and 0.49 y^{-1} for adult male and female albacore tuna, respectively. These results corresponded well to an independent study of tagging data, which estimated a non sex-specific M of 0.45 – 0.5 y^{-1} for north Pacific albacore (Ichinokawa et al. 2008). Based on these results, the ALBWG assumed that the M of juvenile north Pacific albacore tuna followed a Lorenzen (1996) relationship between size and M for age-0 to age-2, with no difference between the sexes until age-3+. Upon reaching age-3, the M for male albacore is assumed to be 0.38 y^{-1} and the M for female albacore is assumed to be higher, reaching 0.49 y^{-1}, which may reflect the cost of reproduction. This age and sex-specific M schedule is an improvement over the previous assumption of a constant M for all ages and sexes because it is based on an analysis of currently available scientific information. However, it should be noted that higher Ms are consistent with a north Pacific albacore stock that is more productive than previously assumed.

4.2.5 Sex specificity

A sex-specific (two sex) model was used for this assessment because of known differences in growth of female and male albacore (Chen et al. 2012, Xu et al. 2014) and natural mortality (Kinney and Teo 2016, Teo 2017a). In addition, males predominate in longline catches of mature albacore sampled scientifically while juveniles <85 cm generally have a sex ratio of 1:1 (Ashida et al. 2016). However, there are currently no data on the sex of individual fish caught by commercial fisheries. As described above, sex-specific growth curves and natural mortality were used in the base case model. However, the base case model did not include sex-specific selectivity, and sex ratio at birth was assumed to be 1:1.

4.2.6 Movement

This stock assessment did not have explicit spatial structure and did not explicitly model the movements of north Pacific albacore. North Pacific albacore are known to exhibit seasonal and

ontogenetic movements (e.g., Ichinokawa et al. 2008, Childers et al. 2011), but it is not currently feasible to develop a spatially explicit assessment model due to the lack of well designed, and consistent tagging data. Instead, selectivity patterns for fisheries were used as a proxy for spatial structure, which helps to compensate for potential biases caused by the lack of explicit spatial structure in the assessment model (Hurtado-Ferro et al. 2014). The collection and pre-processing of fishery data in this assessment are area-specific, especially Japanese longline fisheries, and therefore contain spatial inference (Section 3.3).

4.2.7 Stock structure

The current stock assessment assumes a single stock of albacore in the north Pacific Ocean from the equator to 55°N latitude and between 120°E and 100°W longitude (Fig. 3.2). This assumption is supported by evidence from tagging, and seasonal fishing pattern studies (Suzuki et al. 1977, Ichinokawa et al. 2008, Childers et al. 2011). Studies of albacore population genetics (Chow and Ushiama 1995, Takagi et al. 2001, Montes et al. 2012) support the hypothesis of two stocks in the Pacific Ocean, but do not provide conclusive results on finer scale structure.

4.2.8 Recruitment and reproduction

North Pacific albacore were assumed to have one spawning and recruitment period in the second quarter of the year (Q2) based on recent histological assessments of gonadal status and maturity from the western Pacific Ocean (Chen et al. 2010, Ashida et al. 2016). Although historical circumstantial evidence supported spawning in the central Pacific Ocean near Hawaii through the third quarter of the year (e.g., Otsu and Uchida 1959), there is no recent confirmation of this spawning segment so it was not considered in the assessment. Ashida et al. (2016) also recently estimated the length at 50% maturity for female north Pacific albacore at 86 cm, which was approximately the expected length at age-5. Based on this finding, the ALBWG assumed that 50% of the albacore at age-5 were mature and that all fish age-6+ were mature (Fig. 4.3). This maturity ogive has been used in the previous assessments since 2006 (ALBWG 2014).

A standard Beverton-Holt stock recruitment relationship was used in this assessment. The expected annual recruitment was a function of spawning biomass with steepness (h), virgin recruitment (R_0), and unfished equilibrium spawning biomass (SSB_0) corresponding to R_0, and was assumed to follow a lognormal distribution with standard deviation σ_R (Methot 2000, Methot and Wetzel 2013). Annual recruitment deviations were estimated based on the information available in the data and the central tendency that penalizes the log (recruitment) deviations. A log-bias adjustment factor was used to assure that the estimated log-normally distributed recruitments were mean unbiased (Methot and Taylor 2011).

Recruitment variability (σ_R) was fixed to approximate the expected variability of 0.5. The log of R_0, annual recruitment deviates, and the offset for the initial recruitment relative to virgin recruitment, R_1, were estimated in the base case model. The choice of estimating years with information on recruitment was based on a preliminary model run with all recruitment deviations estimated (1993-2015). The first few years of size composition data often contain some information on recruitment from early cohorts before 1993 and the variability of recruitment deviations often increases as the information content decreases the further back in time prior to starting year examined (Methot and Taylor 2011). The number of years for which recruitments may be observed from the early cohorts was selected and the initial recruitment deviances were estimated in the model. Ten annual deviations were estimated prior to the start of the model in 1993 (i.e., 1983-1992). The 10-year period was chosen because early model runs showed little information on deviates more than 10 years prior to the beginning of the data. Bias adjustment was used to account

for the reduction in information content from the data on recruitment deviations during the early and late periods. This adjustment mostly affects the estimation of uncertainty and not the population trajectory.

Steepness of the stock-recruitment relationship (h) was defined as the fraction of recruitment from a virgin population (R_0) when the spawning stock biomass is 20% of its unfished level (SSB_0). Recently, Lee et al. (2012) concluded that if the model is correctly specified, then steepness is estimable for relatively low productivity stocks with good contrast in spawning stock biomass. However, estimating h within the assessment model for north Pacific albacore is likely to be imprecise and biased because contrast in the spawning biomass over the assessment period is relatively poor. Two independent estimates of steepness for north Pacific albacore (Brodziak et al. 2011, Iwata et al. 2011), based on the life history approach of Mangel et al. (2010), reported values of h ranging from 0.84 to 0.95. Therefore, the ALBWG assumed a steepness value of 0.9 in this assessment, which was the same as the 2014 assessment, and performed sensitivity analyses within a plausible range of steepness values. Nevertheless, the ALBWG notes that these steepness estimates are subject to considerable uncertainty and further work is needed to evaluate steepness estimates.

4.2.9 Initial conditions

A model must assume something about the period prior to the start of the main population dynamics period. Typically, two approaches are used to achieve this assumption. The first approach starts the model as far back as necessary to satisfy the notion that the period prior to the estimation of dynamics was in an unfished or near unfished state. However, this approach is not viable for this assessment because the base case model started in 1993 (Section 2.3.2). Instead, a second approach was used in which initial conditions were estimated (where possible) assuming equilibrium catch. The equilibrium catch is the catch taken from a fish stock when it is in equilibrium with fishery removals and natural mortality balanced by stable recruitment and growth. The initial fishing mortality rates in the assessment model that remove these equilibrium catches were estimated to allow the model to start at an appropriate depletion level. Initial fishing mortality rates were estimated for the F21 (Taiwanese longline in Areas 3 & 5) because it captures a wide size range of albacore, but the initial fishing mortality rates were not fitted to historical catches prior to 1993. This approach allowed the model to start in 1993 at a depletion level that was consistent with the adult abundance index and size composition data without being overly constrained. In addition, the model included estimation of 10 recruitment deviations prior to 1993 to develop a non-equilibrium age structure at the start of the model time frame. A sensitivity run was developed to determine the effect of estimating initial fishing mortality rates for all fisheries by fitting to the average catch before 1993 (Section 5.6.8).

4.3 Fishery Dynamics

4.3.1 Selectivity

The base case model has a sex-specific structure, with sex-specific growth curves. However, it was assumed that female and male albacore have identical size selectivity for each fishery because sex-specific size composition data were not available. Selectivity curves were fishery-specific and assumed to be a function of only size for all but three fisheries. Preliminary model runs indicated that size composition data of the Japanese pole-and-line fisheries in Area 3 (F16 and F17) and the EPO surface fishery (F27) had very strong modes corresponding to juvenile age classes and could not be adequately fit using only size selectivity curves. Therefore, the selectivity curves of F16, F17, and F27 were assumed to be a product of size and age, which improved model fits. The age-based

selectivity was applied to surface fisheries operating north of 30°N and is intended to capture differences in the availability of juvenile fish to the fishing gear based on movement patterns which may vary between seasons and years. Selectivity curves were estimated for all fisheries with representative size composition data while selectivity curves for fisheries without representative size composition data were assumed to be the same as fisheries with similar operating characteristics (season, area, gear) and estimated selectivity curves. If specific fisheries had changes in fishery operations or exhibited changes in size composition data consistent with changes in movement patterns, then selectivity was allowed to vary with time to account for these changes. Highlights of the parameterization of the selectivity curves are briefly described below but more details can be found in Tables 4.2, 4.3, and 4.4.

Selectivity curves for longline fisheries and the Japanese pole-and-line fishery in Area 2 (F18) were assumed to be dome-shaped, and were modeled using either double-normal functions (F2, F4, F9, F10, F15, F18, F19, F20, and F21) or spline functions (F1, F3, and F13), depending on the size data and model fit. (Table 4.2) Fisheries were first fitted with double-normal functions but F1, F3, and F13 were found to have inadequate model fits with this approach. These three fisheries were subsequently fit with spline functions, which are substantially more flexible. The double-normal selectivity functions were configured to use four parameters: 1) peak, which is the initial length at which albacore were fully selected; 2) width of the plateau at the top; 3) width of the ascending limb of the curve; and 4) width of the descending limb of the curve. If the estimated width of the plateau at the top was negligible and tended to hit the lower bounds, then that parameter was fixed at a small value. The spline selectivity functions were configured to be three knot splines. The first and third knots were generally located near the edges of the respective size compositions, while the second knot was typically located near the midpoint between the first and third knot. However, the locations of the knots were subject to some trial and error. The values of two of the three knots were estimated relative to the value of the third knot, which was fixed at an arbitrary value. The gradients before the first knot and after the third knot were also estimated.

Selectivity curves of the Japanese pole-and-line fisheries in Area 3 (F16 and F17) and the EPO surface fishery (F27) were assumed to be a product of size and age because their size composition data exhibited very strong modes corresponding to juvenile age classes (Table 4.3). The size selectivity curves for these fisheries were assumed to be dome-shaped and were modeled using double normal functions, which were configured as described above. The age selectivity of the juvenile age-classes (age-1 through age-5) of these three fisheries were estimated as free parameters. If the age selectivity parameter of an age class hit the upper or lower bound, that parameter was fixed at the upper or lower bound during the final model run to stabilize the optimization of the model. The interactions between the age and size selectivity functions for these three fisheries were difficult to envision but resulted in substantially improved fits to their size composition data.

The selectivity curves for fisheries lacking representative size composition data (F5, F6, F7, F8, F11, F12, F14, F22, F23, F24, F25, F26, F28, and F29) were assumed to be the same as (i.e., mirrored to) closely related fisheries or fisheries operating in the same area (Table 4.4). For example, the selectivity of F5 was assumed to be the same as F1 because F5 was identical to F1 except for their catch units (Table 3.1).

Selectivity curves for relative abundance indices were assumed to be the same as the fishery from which each respective index was derived. Size selectivity for the S1 index was assumed to be the same as the F9 longline fishery. Selectivity for the juvenile albacore index used in sensitivity model runs was similarly assumed to be the same as the F17 Japanese pole-and-line fishery.

Selectivity curves were allowed to vary over time for fisheries exhibiting important changes in fishery operations or if large changes in fish availability during certain periods were observed as changes in the size composition data. Due to the shortened modeling period (1993–2015) for this assessment, only three fisheries (F19, F20, and F27) had time-varying selectivity (Tables 4.2 and 4.3). The US longline fisheries (F19 and F20) had major regulatory changes during 2001 to 2005 to mitigate turtle bycatch, which likely affected fishing operations after 2005. The fishing operations of the EPO surface fishery were found to have changed after 1998, with the fishery moving closer to the US West Coast during and after 1999 (Xu et al. 2013).

4.3.2 Catchability

Catchability, q, was estimated (solved analytically) assuming the abundance index was proportional to vulnerable biomass with a scaling factor of q. It was assumed that q was constant over time for each index.

4.4 Data Observation Models

The current assessment model fitted three data components: 1) total catch, 2) relative abundance indices, and 3) size composition data. The observed total catches were assumed to be unbiased and relatively precise, and were fitted assuming a lognormal error distribution with standard error (SE) of 0.05. An unacceptably poor fit to catch occurred if a model removed <99% of the observed total catch from any fishery.

The relative abundance indices were assumed to have lognormally distributed errors with SE in log space, which is approximately equivalent to CV (SE/estimate) in natural space. The estimated CVs of each index in this assessment were described in their respective papers (Kinoshita et al. 2017, Ochi et al. 2017) (Table 3.2). However, the reported CVs for the abundance indices only capture observation errors within the standardization model and do not reflect process errors that are inherent in the link between the unobserved vulnerable population and observed abundance indices. As in 2014, the ALBWG initially assumed that the minimum average CV for any index was 0.2 and indices with average CV <0.2 were scaled to CV=0.2 by adding a constant while indices with CV >0.2 were left unmodified. Therefore, a constant of 0.101854 was added to the CVs of the S1 index in the base case model, and 0.05365 to the CV of the Japanese pole-and-line index in sensitivity model runs.

The size composition data were assumed to have multinomial error distributions with the error variance determined by the effective sample size (*effN*). Size measurements of fish are usually not random samples of fish from the entire population, but are instead highly correlated within each set or trip (Pennington et al. 2002). The effective sample size is usually substantially lower than the actual number of fish measured because the variance within each set or trip is substantially lower than the variance within a population. The initial effective sample size was set to the number of trips from which fish were measured to account for the lower variance within a trip relative to the population. Since many albacore fisheries do not record the number of trips, an analysis of the US longline fisheries (F19 and F20) was used to relate the number of fish or sets sampled to the number of trips. Based on this analysis, we assumed that 17.7 fish per trip were sampled for the other fisheries. Size composition records with <3 sample sizes were considered unrepresentative and removed. The input sample sizes for each fishery were further rescaled by a multiplier so that the average input sample size for each fishery was approximately the same as for the US longline fisheries (~7).

4.5 Data Weighting

Statistical stock assessment models fit a variety of data components, including abundance indices and size composition data. The results of these models can depend substantially on the relative weighting between different data components (Francis 2011). A statistical approach using the maximum likelihood estimates of variances or effective sample sizes to weight each data component by model fit (Deriso et al. 2007, Maunder 2011) tends to put too much weight on size composition data because numerous important processes such as variability in movements and selectivity are often not modeled or mis-specified. As a result, many assessments now weight different components based on expert knowledge of the data sampling, fishery operations, and biology of the stock, in order to balance or prioritize information from various data components.

Relative abundance indices were prioritized in this assessment based on the principle that relative abundance indices should be fitted well and that other data components such as size composition data should not induce poor fits to the abundance indices because abundance indices are a direct measure of population trends and scale (Francis 2011). Preliminary models indicated that the size composition data from several of the longline fisheries (F9, F10, F13, F19 and F20) degraded the fit of the S1 abundance index, especially relative to the ASPM model fit to the index (ALBWG 2017). The weightings to the size composition data from these five fisheries were down-weighted by multiplying the likelihoods of these data by 0.1 (i.e., lambda = 0.1). Down-weighting these size compositions resulted in model fits to the S1 abundance index that were roughly similar to the ASPM (ASPM S1 likelihood = -26.6; base case S1 likelihood = -25.5) (see Section 5.2.3 to compare base case model fits to the S1 index relative to the ASPM). The effect of these data weightings on model results was investigated using sensitivity runs.

4.6 Model Diagnostics

Model diagnostics were used to assess issues associated with convergence, model structure, parameter mis-specification, and data conflicts in the 2017 base case model. The following diagnostic tools were employed in this assessment: 1) model convergence tests, 2) Age-Structured Production Model (ASPM) diagnostic, 3) R_0 likelihood profiles, 4) residual analysis, and 5) retrospective analysis.

4.6.1 Model convergence

Convergence to the global minima was examined by changing initial parameter values and the order of phases used in the optimization procedure. Particular attention was placed on the initial value and estimation phase of parameters, such as R_0, that influence population scale because these changes force the model to search over a vastly expanded portion of the likelihood surface. In addition, all initial parameter values were randomly jittered by sampling from a uniform distribution centered at input parameter values with upper and lower bounds of $\pm 10\%$. The optimized likelihood and R_0 values were examined from 50 such model runs to ensure that these model runs did not find a solution with better likelihoods.

4.6.2 Age-Structured Production Model (ASPM) diagnostic

Following the proposal by Maunder and Piner (2015), the base case model was modified into an ASPM to identify whether the catch and S1 abundance index were consistent with the estimated scale and trends in the population. Maunder and Piner (2015) stated that "When catch does explain indices with good contrast (e.g., declining and increasing trends), it suggests that a production function is apparent in the data, therefore providing evidence that the index is a reasonable proxy

of stock trend". In this assessment, the base case model was modified by fixing the stock-recruitment relationship, sex-specific growth curves, and selectivities of all fleets to those estimated in the base case model, not estimating annual recruitment deviates so that recruitment follows the stock recruitment curve, and not fitting to the size composition data.

4.6.3 Likelihood profile on virgin recruitment (R_0)

Likelihood profiling over virgin recruitment (R_0) was used to examine the influence of each data component on the overall population scale (Lee et al. 2014). The unfished level of recruitment (R_0) is a global scaling parameter in an SS model because it is proportional to unfished biomass. This process is used to assess whether the relative data weightings are appropriate and/or whether the model is mis-specified. The likelihood profile consisted of running a series of models with the $\ln(R_0)$ parameter fixed at a range of values above and below that estimated within the model, and examining the likelihoods of the various data components.

4.6.4 Residual analysis

Model residuals (i.e., differences between observed data and expected values) were examined to evaluate model fit and performance. The residuals were first visually examined for patterns. The variances of residuals were also compared to evaluate the statistical assumptions of the observation model. If the variance of the residuals differs substantially from the assumed variance, then the relative data weightings likely were not appropriate. However, a lack of residual patterns does not ensure that the model is not mis-specified because parameter estimates can change to compensate for the mis-specification (Maunder and Punt 2013).

4.6.5 Retrospective Analysis

Retrospective analysis was used to identify systemic inconsistencies in population estimates given increasing or decreasing data periods. In this assessment, we performed a within-model retrospective analysis by systematically removing the terminal year of data from successive models (1 to 5 years), while maintaining the same model structure between models.

4.7 Sensitivity to Model Assumptions

A series of sensitivity runs were performed to examine the effects of plausible alternative model assumptions on the assessment results, and to aid in the identification of the major axes of uncertainty in this assessment. The sensitivity analyses conducted in this assessment (Table 4.5) can be categorized into three main themes: 1) biology (e.g., natural mortality, steepness); and 2) data (e.g., data weighting, start year, alternative indices); and 3) model structure (e.g., selectivity, equilibrium catch). For each sensitivity run, female spawning stock biomass (SSB), fishing intensity (1-SPR) trajectories, and where appropriate, model fits to the data, were compared.

4.8 Fishery Impact Analysis

The impact of the surface and longline fisheries on SSB was evaluated. The fishery impact analysis was conducted using the parameterization and assumptions of the base case model and dropping the annual catches (1993-2015) and initial equilibrium fishing mortality from the SS base case data file one-by-one and calculating the SSB time series for each scenario. The magnitude of differences in the simulated SSB trajectories with and without fishing indicates the impact of the major fishery types on the female SSB. Due to the model structure, the F28 and F29 gillnet and miscellaneous fisheries are included as part of the surface fisheries.

4.9 Future Projections

Stock projections were used to assess the impact of current fishing intensity on future harvest and stock status. In the 2014 assessment, an R package called SSfuture (Ichinokawa 2011) was used to perform the future projections but SSfuture was unable to handle the sex-specific population structure.

In the 2017 assessment, a new software package (ssfcpp) was therefore developed to perform the future projections (Ijima et al. 2016). The ssfcpp software package is similar in principle to the SS base case model and the SSfuture package used in the 2014 assessment. However, there are several important differences between ssfcpp and the SSfuture package: 1) ssfcpp utilizes a sex-specific population structure; 2) ssfcpp uses model-estimated recruitment uncertainty and autocorrelation instead of resampling the point estimates of recruitment; 3) ssfcpp does not use SS bootstrapping to represent model uncertainty; and 4) ssfcpp is primarily written in C++ but uses the Rcpp package to enable it to work seamlessly with R to improve speed but retain the simplicity of using an R package. Details on ssfcpp can be found in Ijima et al. (2016) and ssfcpp is available for downloading from https://github.com/h-ijima/ssfcpp. It should be noted that ssfcpp incorporates two main sources of uncertainty in the projections: 1) uncertainty in total biomass estimates; and 2) uncertainty in future recruitment. Thus, ssfcpp does not incorporate all of the estimated uncertainty from the base case model into projections.

Two 10-yr projection scenarios, constant $F_{2012-2014}$ and constant catch (average of 2010-2014), were used to evaluate the impacts of fishing on future female SSB. Future recruitment was based on the expected recruitment variability ($\sigma_R = 0.5$) and estimated autocorrelation (R = -0.13) of the recruitment time series (1993 – 2015) in the base case model. The overall sex-specific F-at-age was estimated from the base case model and used (scaled to the appropriate catch in the constant catch scenario) to remove albacore from the appropriate age and sex in the projected populations. Projections started in 2015 and continued for 10 years through 2025. The projected female SSB, catch, and F-multipliers were calculated for each projection. 500 initial populations were simulated by multiplying the estimated proportions-at-age and -sex with a total biomass that was sampled from the estimated distribution of total population size. Each initial population was subsequently projected using 1,000 runs for 10 years. Each run used a 10-year recruitment vector that was sampled from the distribution of expected future recruitment, which incorporated the stock-recruitment relationship, expected recruitment variability, and recruitment autocorrelation. A total of 500 x 1,000 = 500,000 runs were therefore performed for each projection scenario.

5.0 STOCK ASSESSMENT MODELLING RESULTS

5.1 Model Convergence

All estimated parameters in the base case model were within the set bounds and the final gradient of the model was 6.72E-5, which is consistent with a model that converged onto a local or global minimum. Preliminary models results showed that the likelihood surface around the model convergence zone was bumpy and prone to converging onto local minima. The base case model was therefore run from the SS 'par' file, with highly precise initial values for parameters. Based on the results of 50 model runs with different phasing and initial values, the base case model likely converged to a global minimum (i.e., there was no evidence of a lack of convergence to a global minimum) (Fig. 5.1). Total negative log-likelihood from the model run using the phasing and initial parameters from the base case model was -372.919 and the lowest (best) among these runs, and 1 out of 50 model runs also obtained the same negative log-likelihood. In addition, the estimated

virgin recruitments in log-scale [$\ln(R_0)$] were similar from runs with total negative log-likelihoods similar to the base case model. Therefore, even if the base case model had not converged onto the global minima, the results of a model that converged onto the global minima would be highly similar to the base case model presented here.

5.2 Model Diagnostics

5.2.1 Model fit of abundance indices

The base case model fitted the S1 adult abundance index well (Fig. 5.2 and Table 5.1). It was important that the root-mean-squared-error (RMSE) between observed and predicted abundance indices for S1 were <0.2, which was the input CV for these indices, because this was the primary index that provided information on the spawning stock biomass trends. The catchability coefficient (*q*) was solved analytically in the base case model as a single value for each index (Table 5.1).

5.2.2 Model fit of size composition data

Base case model fits to the size composition data were reasonably good. Overall, the model predicted size compositions matched the observations (Fig. 5.3). Examination of the input sample size (input N) and model estimated effective sample size (*effN*) also show reasonably good model fits (Table 5.2). A higher *effN* is consistent with better model fit and a mean *effN* of >30 is a sign of good overall model fit. In addition, the ratios of the harmonic mean of *effN* to the mean of input N were all >1, which is interpreted to mean that the base case input N did not assume less error than is evident in the model fits. Even the fisheries (F9, F10, F13, F19, and F20) that were down-weighted with a lambda of 0.1 had good fits to the size composition data. However, the model fits to the size composition data of two of the Japanese pole-and-line fisheries (F17 and F18), although adequate, had ratios of the harmonic mean of *effN* to the mean of input N that were <2 and could be improved upon in the next assessment.

Pearson residual plots of the model fit to the size composition data did not reveal substantial patterns in residuals (Fig. 5.4). Where patterns were evident visually, the scale of the residuals was generally small, mostly lying within ± 2 standard deviations. The fisheries with the largest Pearson residuals appeared to be the US longline fisheries (F19 and F20), which was likely related to the small number of fish sampled in some strata of the original data (Teo 2017e). It should be noted that the Pearson residual plots of the fisheries with down-weighted size composition data using a lambda of 0.1 (F9, F10, F13, F19, and F20), are unrepresentative of the true residuals. The absolute scale of the plotted residuals are too large because the plotting software did not account for the down-weighted data but the relative scale of the residuals are representative. .

5.2.3 Age-structured production model (ASPM) diagnostic

The ASPM had similar scale and populations trends to the base case model (Fig. 5.5). Model fits of the ASPM to the S1 index was also similar to the base case model (ASPM S1 rsme: 0.150; base case S1 rmse: 0.164; ASPM S1 likelihood: -26.6; base case S1 likelihood: -25.5). These results showed that the estimated catch-at-age and fixed productivity parameters (i.e., growth, natural mortality, and spawner-recruit relationship) were able to explain trends in the S1 index without the addition of process error in the form of annual recruitment deviates. This finding in turn means that the base case model was able to estimate the stock production function and the effect of fishing on the abundance of the north Pacific albacore stock. The connection between catch-at-age and the S1 index adds confidence to the data used, and represents a major improvement from the previous assessment.

5.2.4 Likelihood Profiles on Virgin Recruitment (R_0)

Results of the likelihood profiling on virgin recruitment, R_0, for the abundance indices and size composition data components of the model are shown in Fig. 5.6. Changes in the likelihood of each data component are a measure of how informative that data component is to the overall estimated population scale.

The ASPM diagnostic showed that the S1 abundance index was informative on the estimated population scale, especially the status of the stock with respect to the 20%SSB$_{current, F=0}$ LRP. However, due to the moderate exploitation levels of this stock, the R_0 profile of the S1 abundance index showed that the changes in log-likelihood over the range of R_0 examined was relatively small, which means that the estimated population scale was relatively uncertain. Nevertheless, it is important to note that the negative log-likelihood profile of the S1 abundance index was asymmetrical, with increasing negative log-likelihoods when R_0 was low and relatively little change when R_0 was high. This finding is consistent with an S1 abundance index that is particularly useful for providing information on whether the population is lower than a certain minimum level but less informative on the upper limit to the population scale (i.e., uncertainty was primarily on the high R_0 side). The primary aim of estimating the SSB in this assessment was to determine whether the estimated SSB is lower than the LRP (i.e., determine whether the stock was in an overfished condition). Since the R_0 profiles show that the lower bound is better defined, it adds confidence to the ALBWG's evaluation of stock condition relative to the limit reference point.

The changes in the negative log-likelihood of the size composition data and the estimated R_0 were approximately in the same range as the S1 abundance index, which is expected when the size composition data are appropriately weighted. The size composition data generally constrained the estimated population scale from going too high, in contrast to the S1 index. However, size composition data are generally considered less reliable in estimating population scale.

Overall, the R_0 likelihood profile showed that there was substantial uncertainty in the estimate of population scale of this assessment, which was reflected in the uncertainty in biomass estimates. Nevertheless, the R_0 likelihood profile also showed that the estimated ln(R_0) in the base case model was consistent with all the data components, especially the S1 abundance index, that the ALBWG considered to be important for defining population scale in the assessment model, especially for defining the status of the stock.

Importantly, even when the fit to the S1 index was degraded (increase in log-likelihood of about 1.5) with a ln(R_0) fixed at 11.5 , the ratio of the estimated female SSB relative to unfished SSB remained higher than the 20%SSB$_{current, F=0}$ LRP (Fig. 5.7). Thus, the results of this assessment with respect to the status of the stock, are relatively robust.

5.2.5 Retrospective Analysis

Retrospective analyses did not reveal any important pattern in the estimates of spawning biomass and fishing intensity (1-SPR) with the successive elimination of terminal year data. Removing one to three years of terminal data resulted in negligible changes in the results of the model (Fig. 5.8). However, removing four or five years of terminal years of data resulted in lower estimates of female SSB and higher fishing intensity. This change was not surprising because five years of data in the base case model with 23 years of data is >20% of the available data. Nevertheless, the estimated female SSB from all the models from this analysis remained above the 20%SSB$_{current,F=0}$ LRP, which is consistent with the conclusion that the results of this assessment are relatively robust.

5.3 Model Parameter Estimates

5.3.1 Selectivity

The estimated selectivity of fisheries assumed to have size-only selectivity or a product of size and age selectivity (F16, F17, and F27) are shown in Fig. 5.9 and 5.10, respectively. Although all fisheries with size-only selectivity have nominally dome-shaped selectivity, the peak of the selectivity of some fisheries were so large (e.g., F20) that they acted as fisheries with asymptotic selectivity (Fig. 5.9). The selectivity of the F16, F17 and F27 fisheries were relatively non-intuitive, especially the age selectivity, because the overall selectivities were products of both size and age selection.

The peak and width of the ascending slope parameters for the fisheries with dome-shaped selectivity are typically precisely estimated while the width of the plateau and descending slope parameters have high uncertainty (Table 4.2 and 4.3). The differences in uncertainty of parameters in a double normal selectivity curve is expected because the width of the plateau and descending slope parameters are correlated, which increases the uncertainty in these parameters. It should also be noted that some of the age selectivity parameters for F16, F17 and F27 were also fixed to improve model optimization (Table 4.3).

5.3.2 Catch-at-Age

Juvenile albacore aged 2, 3, and 4 were the largest components of north Pacific albacore catch (Figure 5.11) due to the importance of surface fisheries (primarily troll, pole-and-line, and including other miscellaneous gears).

5.3.3 Sex Ratio

The fraction of females in the population changes by age and length (Fig 5.12). Sex ratio is approximately 1:1 until albacore reach age-3+, after which males becomes more common due to the higher M in females at ages-3+. This change in sex ratio is further accentuated by the differences in growth such that the sex ratio is heavily biased for albacore >100 cm. The heavy bias towards males at large sizes (>100 cm) has been observed in this stock (Fig. 3.6) and in the south Pacific albacore stock (Farley et al. 2013). Although the heavily biased sex ratio of large albacore may have consequences in the estimated population dynamics of this stock, the implications of this bias on estimates of management quantities, stock status determinations or the development of conservation advice, are not known.

5.4 Stock Assessment Results

5.4.1 Biomass

The estimated female SSB fluctuated between 1993 and 2015, with a high of 139,481 ± 55,373 t (±SD) in 1995 and a low of 69,428 ± 27,236 t in 2003 (Fig. 5.13 and Table 5.3). Estimated female SSB was relatively high prior to 2000 but has fluctuated without an obvious trend since 2000. In the terminal year of the assessment (2015), female SSB was estimated to be 80,618 ± 32,275 t. The LRP ($20\%SSB_{current, F=0}$) adopted by the WCPFC is based on dynamic SSB_0 and has fluctuated between 29,560 to 42,352 t during the assessment period. The maximum likelihood estimate of female SSB has therefore been above the LRP throughout the assessment period.

However, uncertainty in the estimated female SSB was relatively large and the 95% confidence intervals overlapped the LRP throughout the assessment period. Uncertainties in the spawning

biomass estimates were relatively large because the virgin recruitment parameter (R_0), which largely determines the population scale, was estimated with a relatively large uncertainty.

The total biomass estimates in the first quarter, which includes all age-1+ male and female albacore, have also fluctuated during the assessment period, ranging from a low of 796,877 t in 2014 to a high of 1,207,150 t in 1994 (Fig. 5.13 and Table 5.3).

5.4.2 Recruitment

Estimated recruitment was generally consistent with the biology of the stock and assumptions in the base case model. Recruitment estimates did not show a substantial trend with respect to female SSB (Fig. 5.13), which was expected because albacore and other tunas have recruitment variability largely driven by environmental conditions, and a steepness of 0.9 was assumed in this assessment (Section 4.2.8). The estimated recruitments were consistent with the expected distribution of recruitment deviations (σ_R = 0.5), where all recruitment estimates were within the expected distribution.

The estimated recruitments have fluctuated widely during the assessment period (1993 – 2015), ranging from a low of 135.3 ± 38.5 million fish (± SD) in 1998 to a high of 307.6 ± 71.1 million fish in 1999 (Figure 5.13 and Table 5.3). The average recruitment during the 1993 – 2015 period was 201.5 million fish, which was slightly below virgin recruitment (226.2 million fish).

Uncertainty in the recruitment estimates was relatively large because uncertainty estimated for the virgin recruitment parameter, which largely determines the population scale, was relatively large. In addition, the uncertainty in the last three years (2013 – 2015) of the assessment were larger than the rest of the time series because the amount of information on recruitment declines towards the end of a model.

5.4.3 Fishing intensity

Spawning potential ratio (SPR) was used to describe the fishing intensity on this stock. The SPR of a population is the ratio of female SSB per recruit under fishing to the female SSB per recruit under virgin (or unfished) conditions. Therefore, 1-SPR is the reduction in female SSB per recruit due to fishing and can be used to describe the overall fishing intensity on a fish stock (Goodyear 1993). The fishing intensity (1-SPR) on the north Pacific albacore stock has fluctuated between 0.28 and 0.61 during the assessment period (1993 – 2015), and was 0.47 in 2015 (Table 5.3).

Fishing mortality-at-age (F-at-age) was estimated for female and male albacore in the base case model (Fig. 5.14). The F-at-age of juveniles was higher than most of the adult age classes, which corresponds to the larger catches of the surface fisheries. The F-at-age for adult females was lower than for adult males because of sex-specific differences in natural mortality and size-at-age for adult albacore.

5.5 Biological Reference Points

Kobe plots are presented in Figure 5.15 to illustrate the stock status of the north Pacific albacore stock in relation to the biomass-based LRP adopted by the WCPFC ($20\%SSB_{current, F=0}$) and the equivalent fishing intensity ($1\text{-}SPR_{20\%}$) for the LRP. Limit reference points for fishing intensity or F-based reference points for north Pacific albacore have not been adopted by either the IATTC or WCPFC. The Kobe plot for the base case model shows that the stock has not fallen below the LRP during the assessment period. However, there is substantial uncertainty in the estimated female SSB and accompanying stock status. Even when alternative hypotheses about key uncertainties

such as natural mortality and growth are evaluated (Section 5.6), the point estimate of female spawning biomass does not fall below the LRP, although risk of being below increases with some assumptions, i.e., the relative proportion of the error bars below the LRP increase (Fig. 5.15).

Biological reference points were computed from the base case model (Table 5.4). The point estimate (± SD) of maximum sustainable yield (MSY – which includes male and female juvenile and adult fish) was 132,072 t and the point estimate of female SSB to produce MSY (SSB_{MSY}) is 24,770 t. Current F ($F_{2012-2014}$) was defined as the average 1-SPR for the years 2012-2014 because terminal year estimates of fishing intensity were generally considered to be uncertain. Current SSB (SSB_{2015}) was defined as the female SSB in 2015. The ratio of $F_{2012-2014}/F_{MSY}$ was estimated to be 0.61 and the ratio of $SSB_{2015}/20\%SSB_{current, F=0}$ was estimated to be 2.47. Current F is below F_{MSY} and all MSY-proxy reference points except $F_{50\%}$, and SSB_{2015} is well above the LRP threshold (Table 5.4). Note that $F_{2012-2014}$ and F-based reference points were not based on the average instantaneous fishing mortality. Instead, $F_{2012-2014}$ and F-based reference points were indices of fishing intensity based on SPR and calculated as 1-SPR so that they reflected changes in fishing mortality.

5.6 Sensitivity to Model Assumptions

The following sensitivity analyses were performed to examine the effects of plausible alternative model assumptions on the assessment results, and help identify the major axes of uncertainty in this assessment (see Table 4.4 for details).

5.6.1 Sensitivity 01 – Natural mortality

Natural mortality is typically considered to be a major axis of uncertainty in most stock assessments. In addition, the sex-specific M-at-age vector used in this assessment was a major change from the 2014 assessment (Section 2.3.3). Therefore, sensitivity model runs were performed using a constant M of 0.3 y^{-1} for both sexes and all ages (as in the 2014 assessment), and a constant M of 0.38 and 0.49 y^{-1} for males and females, respectively, of all ages. Changing the M from 0.3 y^{-1} in the 2014 assessment to the sex-specific M-at-age vector in this assessment resulted in major differences in the estimated spawning biomass depletion, and fishing intensity (1-SPR) of the assessment (Fig. 5.16). The differences were primarily due to the changes in the M at age-3+ rather than the M at ages-0 to 2. Natural mortality was considered to be the most important axis of uncertainty in this assessment.

5.6.2 Sensitivity 02 – Steepness

Steepness of the Beverton-Holt stock-recruitment relationship also is considered a major axis of uncertainty in most stock assessments. Sensitivity model runs were performed using alternative steepness values (h = 0.75; 0.80; and 0.85) to the base case model (h = 0.90). However, changing the steepness values had very limited effect on the estimated scale or trends in female SSB, spawning biomass depletion, and fishing intensity (Fig. 5.17). A similar result was reported in the 2014 assessment.

5.6.3 Sensitivity 03 – Growth

Growth was considered the most important axis of uncertainty in the 2014 assessment because the previous assessment included size composition data from the 1980s and early 1990s, when a high proportion of very large albacore were present in the size composition data from Japanese longline fisheries. The same sex-specific growth model from the 2014 assessment was used in this assessment. The model fits to the size composition data were substantially improved in this assessment, but there remained uncertainty in the growth model, especially the CV of the L_{inf}

parameter. Sensitivity runs were performed with the CVs of the L_{inf} parameter (CV = 0.06; and 0.08) that were larger than those parameter values in the base case model (CV = 0.04). A sensitivity using the Richards growth model was developed but failed to converge, and was therefore not considered further. Changing the CVs on the L_{inf} parameter had major effects on the scale of estimated female SSB, spawning depletion, and fishing intensity, with larger CVs leading to lower estimated SSB (Fig. 5.18). Growth was considered to be an important axis of uncertainty in this assessment.

5.6.4 Sensitivity 04 – Start year

One of the major changes in this assessment compared to the 2014 assessment was the change in the start year from 1966 to 1993 (Section 2.3.2). A sensitivity with a start year of 1966 was developed to illustrate the sensitivity of model results to this change. However, there were difficulties in fitting the size composition data from the Japanese longline fisheries in the 1980s and early 1990s. Therefore, the ALBWG developed a sensitivity that was fitted to the adult abundance indices associated with the F9 fishery during 1976-1992 and 1996-2015; and included the catch from all fisheries for 1966-2015; but only fitted to the size composition data from 1993-2015. The selectivity of the fisheries during 1966-1992 was assumed to be the same as for the base case model. Changing the start year in this manner did not substantially change the scale or trends in estimated female SSB, spawning biomass depletion, and fishing intensity (Fig. 5.19).

5.6.5 Sensitivity 05 – Juvenile index

In contrast to previous assessments, the base case model of the 2017 assessment was not fitted to the Japanese pole-and-line indices as measures of juvenile abundance trends (Section 2.3.1). Therefore, a sensitivity, which was fitted to the Japanese pole-and-line index from the F17 fishery, was developed to illustrate the effect of this decision on the assessment results. Fitting to the F17 index resulted in a much larger female SSB and lower fishing intensity (Fig. 5.20). However, the fit to the F17 index was relatively poor and the estimated spawning depletion was unreasonably high (>1.0). Combined with the reasons highlighted in Sections 2.3.1 and 3.5.2 that explained why the base case model was not fitted to the F17 index, the results of this sensitivity were not considered plausible.

5.6.6 Sensitivity 06 – Size composition weighting

The size composition data of five fisheries (F9, F10, F13, F19, and F20) were down-weighted with a lambda of 0.1 in this assessment (Section 4.5), while the size composition data from the rest of the fisheries were left at their natural weights (lambda = 1.0). Therefore, sensitivity models were developed where the size composition data of all fisheries were either down-weighted (lambda = 0.1) or at their natural weight (lambda = 1.0), respectively. The size composition data weighting did not substantially affect either trends or scale of the estimated female SSB, spawning depletion, and fishing intensity (Fig. 5.21). The ALBWG concluded that the results of the assessment were robust to the weighting of the size composition data.

5.6.7 Sensitivity 07 – US longline asymptotic selectivity

All fisheries were allowed to have a dome-shaped selectivity and all estimated size selectivity appeared to be dome-shaped in the base case model. Stock assessments without a fishery assumed to have an asymptotic selectivity may result in an unrealistically large estimated SSB (i.e., cryptic biomass) because not all fish are selected. A sensitivity model was developed where the F20 US longline fishery, which catches the largest albacore, was assumed to have asymptotic selectivity instead of being allowed to estimate a dome-shaped selectivity. Assuming an asymptotic selectivity

for the F20 US longline fishery resulted in negligible differences in the scale and trends of estimated female SSB, spawning depletion, and fishing intensity (Fig. 5.22).

5.6.8 Sensitivity 08 – Equilibrium catch

Initial conditions of the model in this assessment were relatively freely estimated from the data in the main model period (1993 – 2015). Although the initial fishing mortality of a fishery (F21) was estimated, the equilibrium catch prior to the modelling period was not fitted. A sensitivity model was developed where the initial F of all major fisheries were estimated and the equilibrium catch of these fisheries were fitted. The equilibrium of each fishery was calculated as the average of 10 years of annual catch during 1983 – 1992. Equilibrium catch of fisheries that were ≤50 t or ≤25,000 fish were assumed to be negligible. Fitting to the equilibrium catch did not result in major differences in the estimated female SSB, spawning depletion, and fishing intensity (Fig. 5.23)

5.6.9 Sensitivity 09 – 2014 base case model structure

The model structure of the base case model for this assessment had several important changes from the 2014 base case model (Section 2.3). A sensitivity model that followed as close as possible the model structure of the 2014 base case model was developed. Importantly, this sensitivity model had a start year of 1966, an M of 0.3 y^{-1} for both sexes, down-weighted all size composition data, and fitted to a Japanese pole-and-line index (1975 – 2015). Following the model structure of the 2014 base case model resulted in a higher female SSB and different SSB trends (Fig. 5.24). The difference is likely due to fitting to the Japanese pole-and-line abundance index. However, given the reasons highlighted in Sections 2.3 and the lack of model diagnostics in this sensitivity model, the results of this sensitivity model were not considered plausible. In addition, the estimated spawning depletion and fishing intensity around the terminal year was relatively similar to the base case model in this assessment.

5.7 Fishery Impact Analysis

Surface fisheries (primarily troll, and pole-and-line, but including gillnet and other miscellaneous gears), which tend to catch juvenile fish, have generally had a larger impact on the north Pacific albacore stock than longline fisheries, which tend to remove adult fish (Fig. 5.25) at a ratio of about 2:1.

5.8 Future Projections

The constant fishing intensity and constant catch projection scenarios show that the current fishing intensity ($F_{2012-2014}$) is expected to reduce female SSB to 63,483 t (CI: 36,046 - 90,921 t) by 2025, with a 0.2 and <0.01 % probability of being below the LRP by 2020 and 2025, respectively (Fig. 5.26). Median catch is expected to increase in 2017 and 2018 and then decline to about 60,000 t in 2024 when fishing at $F_{2012-2014}$ (Fig. 5.26). However, median future catch is expected to be below the average catch level for 2010-2014 (82,432 t – red line in Fig. 5.26). This result is most likely due to low estimated recruitment in 2011, which is expected to reduce female SSB beginning in 2015, the first year of the projection period. In contrast, employing the constant catch harvest scenario is expected to reduce female spawning biomass to 47,591 t (CI: 5,223 - 89,958 t) by 2025 and increases the probability that female SSB will be below the LRP to about 3.5 and 30 % in 2020 and 2025, respectively (Fig. 5.27). The probabilities of female SSB falling below the LRP may be higher than estimated in these scenarios because the software does not incorporate all the estimated uncertainty from the base case model into the projections. It should be noted that the constant

catch scenario is inconsistent with current management approaches for north Pacific albacore tuna adopted by the IATTC and the WCPFC.

6.0 STOCK STATUS

6.1 Current Status

Estimated total stock biomass (males and female at age-1+) declines at the beginning of the time series until 2000, after which biomass becomes relatively stable (Fig. 5.13A). Estimated female SSB exhibits a similar population trend, with an initial decline until 2003 followed by fluctuations without a clear trend through 2015 (Fig. 5.13B). The estimated SPR (spawners per recruit relative to the unfished population) in 2015 is 0.53, which corresponds to a moderate exploitation intensity (i.e., 1-SPR = 0.47). Instantaneous fishing mortality at age (F-at-age) is similar in both sexes through age-5, peaking at age-4 and declining to a low at age-6, after which males experience higher F-at-age than females up to age 13 (Fig. 5.14). Juvenile albacore aged 2 to 4 years comprised, on average, 70% of the annual catch between 1993 and 2015 (Fig. 5.11) as reflected by the larger impact of the surface fisheries (primarily troll, pole-and-line) which remove juvenile fish, relative to longline fisheries, which primarily remove adult fish (Fig. 5.25).

The Western and Central Pacific Fisheries Commission (WCPFC) adopted a limit reference point (LRP) for the spawning stock biomass of 20% of the spawning stock biomass when F=0 ($20\%SSB_{current, F=0}$) (https://www.wcpfc.int/harvest-strategy). The $20\%SSB_{current, F=0}$ LRP is based on dynamic biomass and fluctuates depending on changes in recruitment. However, there are no adopted F-based limit reference points.

Stock status is depicted in relation to the limit reference point (LRP; $20\%SSB_{current, F=0}$) for the stock and the equivalent fishing intensity ($F_{20\%}$; calculated as $1-SPR_{20\%}$) (Fig. 5.15). Fishing intensity (F, calculated as 1-SPR) is a measure of fishing mortality expressed as the decline in the proportion of the spawning biomass produced by each recruit relative to the unfished state. For example, a fishing intensity of 0.8 will result in a SSB of approximately 20% of SSB_0 over the long run. Fishing intensity is considered a proxy of fishing mortality.

The Kobe plot shows that the estimated female SSB has never fallen below the LRP since 1993, albeit with large uncertainty in the terminal year (2015) estimates. Even when alternative hypotheses about key model uncertainties such as natural mortality and growth were evaluated, the point estimate of female SSB in 2015 (SSB_{2015}) did not fall below the LRP, although the risk increases with these more extreme assumptions (Fig. 5.15). The SSB_{2015} was estimated to be 80,618 t and was 2.47 times greater than the LRP threshold of 32,614 t (Table 5.4). Current fishing intensity, $F_{2012-2014}$ (calculated as $1- SPR_{2012-2014}$), was lower than potential F-based reference points identified for the north Pacific albacore stock, except $F_{50\%}$ (calculated as $1-SPR_{50\%}$) (Table 5.4).

Based on these findings, the following information on the status of the north Pacific albacore stock is provided:

1. The stock is likely not overfished relative to the limit reference point adopted by the Western and Central Pacific Fisheries Commission ($20\%SSB_{current\ F=0}$), and

2. No F-based reference points have been adopted to evaluate overfishing. Stock status was evaluated against seven potential reference points. Current fishing intensity ($F_{2012-2014}$) is below six of the seven reference points (see ratios in Table 5.4), except $F_{50\%}$.

6.2 Conservation Information

Two harvest scenarios were projected to evaluate impacts on future female SSB: F at the 2012-2014 rate over 10 years ($F_{2012-2014}$) and constant catch[3] (average of 2010-2014 = 82,432 t) over 10 years. Median female SSB is expected to decline to 63,483 t (95% CI: 36,046 - 90,921 t) by 2025, with a 0.2 and <0.01% probability of being below the LRP by 2020 and 2025, respectively, if fishing intensity remains at the 2012-2014 level[4] (Fig. 5.26). In contrast, employing the constant catch harvest scenario is expected to reduce female SSB to 47,591 t (95% CI: 5,223 - 89,958 t) by 2025 and increases the probability that female SSB will be below the LRP to about 3.5 and 30% in 2020 and 2025, respectively (Fig. 5.27). In addition, as biomass declines during the projection period the fishing intensity approximately doubles by 2025. Although the probabilities of declining below the LRP in both harvest scenarios are likely higher in the future, even the most extreme results from other model runs with plausible alternative assumptions show that female SSB is not likely to have declined below the LRP throughout the assessment period (1993 – 2015).

Based on these findings, the following information is provided:

1. If a constant fishing intensity ($F_{2012-2014}$) is applied to the stock, then median female spawning biomass is expected to decline and there will be < 0.01% probability of falling below the limit reference point established by the WCPFC by 2025. However, expected catches will be below the recent average catch level for this stock[4].
2. If a constant average catch ($C_{2010-2014}$ = 82,432 t) is removed from the stock in the future, then the decline in median female spawning biomass will be greater than in the constant F scenario and the probability that SSB falls below the LRP will be greater by 2025 (30%). Additionally, the estimated fishing intensity will double relative to the current level ($F_{2012-2014}$) by 2025 as spawning biomass declines.

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[3] It should be noted that the constant catch scenario is inconsistent with current management approaches for north Pacific albacore tuna adopted by the Inter-American Tropical Tuna Commission (IATTC) and the WCPFC.

[4] Median future catch for the constant F scenario is expected to be below the average catch level for 2010-2014 (82,432 t – red line in Fig. 5.26). This result is most likely due to low estimated recruitment in 2011, which is expected to reduce female SSB beginning in 2015, the first year of the projection period.

7.0 KEY UNCERTAINTIES AND RESEARCH RECOMMENDATIONS

The ALBWG noted that the lack of sex-specific size data, shortened modeling period, and the simplified treatment of the spatial structure of north Pacific albacore population dynamics were important sources of uncertainty in the assessment. The following recommendations were developed to improve the future iterations of the stock assessment model:

1. Further investigation of sex-specific growth is required with respect to the model and the inclusion of growth increment data from tagging (change in size between release and recapture) and otolith data in the growth model;
2. Evaluate the use of Japan longline juvenile index from northern areas to represent juvenile albacore trends rather than the Japan pole-and-line index;
3. Investigate incorporating the early period (1966-1992) back into the model and address the data conflict during this period;
4. Evaluate sampling protocols and accuracy of historical and current size frequency data (length and weight) for all fleets, including Japan training vessels;
5. Standardizing size composition data to the CPUE index that they represent;
6. Collect high quality samples for development of genetic sex markers;
7. The collection of sex ratio data by fleet should be implemented;
8. Explore the utility of conventional and electronic tagging (archival and PSAT) data to inform growth, catchability, spatial dynamics in future models; and
9. Explore ocean productivity as drivers of albacore trends and dynamics.

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TABLES

Table 3.1. Fishery definitions for the 2017 assessment of north Pacific albacore tuna. Availability of size and abundance index data is indicated in the notes. * indicates that size or index data were available but were not fitted in the base case model. Two letter country codes are used in the fishery name: JP = Japan; US = United States of America; TW = Chinese-Taipei; KR = Korea; and VU = Vanuatu.

ID	Fishery name	Area	Primary gear	Quarter	Catch unit	Notes
F1	F1_JPLL_A13_Q1_wt	1 & 3	Longline	1	Tonnes	Size
F2	F2_JPLL_A13_Q2_wt	1 & 3	Longline	2	Tonnes	Size
F3	F3_JPLL_A13_Q3_wt	1 & 3	Longline	3	Tonnes	Size
F4	F4_JPLL_A13_Q4_wt	1 & 3	Longline	4	Tonnes	Size
F5	F5_JPLL_A13_Q1_num	1 & 3	Longline	1	1000s	
F6	F6_JPLL_A13_Q2_num	1 & 3	Longline	2	1000s	
F7	F7_JPLL_A13_Q3_num	1 & 3	Longline	3	1000s	
F8	F8_JPLL_A13_Q4_num	1 & 3	Longline	4	1000s	
F9	F9_JPLL_A2_Q1_wt	2	Longline	1	Tonnes	Size, Index
F10	F10_JPLL_A2_Q234_wt	2	Longline	2, 3 & 4	Tonnes	Size
F11	F11_JPLL_A2_Q1_num	2	Longline	1	1000s	
F12	F12_JPLL_A2_Q234_num	2	Longline	2, 3 & 4	1000s	
F13	F13_JPLL_A4_wt	4	Longline	All	Tonnes	Size
F14	F14_JPLL_A4_num	4	Longline	All	1000s	
F15	F15_JPLL_A5_num	5	Longline	All	1000s	Size
F16	F16_JPPL_A3_Q12	3	Pole & line	1 & 2	Tonnes	Size
F17	F17_JPPL_A3_Q34	3	Pole & line	3 & 4	Tonnes	Size, Index*
F18	F18_JPPL_A2	2	Pole & line	All	Tonnes	Size
F19	F19_USLL_A35	3 & 5	Longline	All	Tonnes	Size
F20	F20_USLL_A24	2 & 4	Longline	All	Tonnes	Size
F21	F21_TWLL_A35	3 & 5	Longline	All	Tonnes	Size
F22	F22_TWLL_A24	2 & 4	Longline	All	Tonnes	
F23	F23_KRLL	All	Longline	All	Tonnes	Size*
F24	F24_CNLL_A35	3 & 5	Longline	All	Tonnes	
F25	F25_CNLL_A24	2 & 4	Longline	All	Tonnes	Size*
F26	F26_VULL	All	Longline	All	Tonnes	Size*
F27	F27_EPOSF	3 & 5	Surface	All	Tonnes	Size
F28	F28_JPKRTW_DN	All	Drift net	All	Tonnes	
F29	F29_JPTW_MISC	All	Misc	All	Tonnes	

Table 3.2. Standardized values and input coefficients of variation (CVs) of north Pacific albacore annual abundance indices developed for the 2017 base case model (S1) and sensitivity runs (Japanese pole-and-line). Units are number of fish (S1) and weight (Japanese pole-and-line; F17). Quarter refers to annual quarters in which the majority of catch was made in the underlying fishery, where 1 = Jan-Mar, 2 = Apr-June, 3 = July-Sept, and 4 = Oct-Dec. A constant of 0.101854 was added to the CVs of the S1 index in the base case model, and 0.05365 to the CV of the Japanese pole-and-line index in sensitivity model runs, to raise the average CV to 0.2. CV values shown here do not include these constants.

Year	S1 – Japanese longline in Area 2, Quarter 1		Japanese pole-and-line in Area 3 Quarter 3 (sensitivity runs only)	
	CPUE	CV	CPUE	CV
1993			1.236185	0.125647
1994			2.639997	0.171094
1995			2.091945	0.157335
1996	36.9117	0.100121	1.072426	0.161214
1997	41.2489	0.100040	1.569386	0.226785
1998	43.4061	0.099416	1.496286	0.189806
1999	33.3219	0.095808	1.966411	0.167172
2000	45.0808	0.099295	0.920254	0.178656
2001	40.5251	0.098520	1.325804	0.214235
2002	26.9308	0.102563	3.114004	0.260182
2003	29.6747	0.092728	1.163449	0.166174
2004	21.4468	0.100538	0.358221	0.120884
2005	28.8161	0.099267	0.751029	0.134833
2006	30.9491	0.091277	0.284576	0.108623
2007	27.4267	0.094014	0.166831	0.106892
2008	28.6204	0.097362	0.187657	0.110984
2009	28.8633	0.095085	0.368099	0.123472
2010	34.1064	0.091093	0.628833	0.118937
2011	26.4014	0.099881	0.484458	0.108889
2012	27.2031	0.099221	0.61616	0.133060
2013	25.9731	0.105268	0.333396	0.111130
2014	19.4698	0.100825	0.270034	0.120775
2015	33.7446	0.100591	0.193324	0.117711

Table 4.1. Key life history parameters and model structures used in the base case model.

Parameter	Value	Comments	Source
Natural mortality (M)	Female age-0: 1.36 y^{-1} Female age-1: 0.56 y^{-1} Female age-2: 0.45 y^{-1} Female age-3+: 0.48 y^{-1} Male age-0: 1.36 y^{-1} Male age-1: 0.56 y^{-1} Male age-2: 0.45 y^{-1} Male age-3+: 0.39 y^{-1}	Fixed parameter.	Teo (2017a)
Length at age-1 (L_1)	Female: 43.504 cm Male: 47.563 cm	Fixed parameter	Xu et al. (2014)
Asymptotic length (L_{inf})	Female: 106.57 cm Male: 119.15 cm	Fixed parameter	Xu et al. (2014)
Growth rate (k)	Female: 0.29763 y^{-1} Male: 0.20769 y^{-1}	Fixed parameter	Xu et al. (2014)
CV of L_1	0.06	Non sex-specific, fixed parameter	ALBWG (2014)
CV of L_{inf}	0.04	Non sex-specific, fixed parameter	ALBWG (2014)
Weight-at-length – Q1	W_L (kg) = 8.7 * 10^{-5} L (cm) $^{2.67}$	Non sex-specific, fixed parameters	Watanable et al. (2006)
Weight-at-length – Q2	W_L (kg) = 3.9 * 10^{-5} L (cm) $^{2.84}$	Non sex-specific, fixed parameters	Watanable et al. (2006)
Weight-at-length – Q3	W_L (kg) = 2.1 * 10^{-5} L (cm) $^{2.99}$	Non sex-specific, fixed parameters	Watanable et al. (2006)
Weight-at-length – Q4	W_L (kg) = 2.8* 10^{-5} L (cm) $^{2.92}$	Non sex-specific, fixed parameters	Watanable et al. (2006)
Maturity	50% at age-5, 100% age-6+	Fixed parameters	Ueyanagi (1957); Chen et al. (2016);
Fecundity	Proportional to spawning biomass	Fixed parameters	Ueyanagi (1957)
Spawning season	2	Model structure	Ueyanagi (1957); Chen et al. (2010); Ashida et al. (2016)
Spawner-recruit relationship	Beverton-Holt	Model structure	
Spawner-recruit	0.9	Fixed parameter	Brodziak et al.

Parameter	Value	Comments	Source
steepness (h)			(2011); Iwata et al. (2011); ALBWG (2014)
Log of Recruitment at virgin biomass $\ln(R_0)$	12.3293	Maximum likelihood estimate	
Recruitment variability (σ_R)	0.5	Fixed parameter	
Initial age structure	10 y	Estimated	
Main recruitment deviations	1993-2015	Estimated	
Selectivity	Size selectivity only (splines): F1, F3, & F13 Size selectivity only (dome): F2, F4, F9, F10, F15, F18, F19, F20, & F21 Size and age selectivity: F16, F17, & F27 Shared selectivity: F5, F6, F7, F8, F11, F12, F14, F22, F23, F24, F25, F26, F28, & F29	Estimated (see Table 4.2)	
Catchability		Solved analytically	

Table 4.2. Selectivity parameters used in the base case model for fisheries with only size selectivity. Estimated parameters are shown in bold, with estimated standard deviation in parentheses. The optional initial and final parameters for all double-normal selectivity curves were fixed at -999 and ignored by the model. The value for the first knot for all spline selectivity curves were fixed at 0 and values for the second and third knot were estimated relative to that. Knot locations in cm are indicated in parentheses in the years column.

Size selectivity (double-normal)					
Fishery	Years	Parm 1 – Size at peak	Parm 2 – Plateau width	Parm 3 – Ascending slope	Parm 4 – Descending slope
F2	1993 – 2015	**79.85 (1.25)**	-9	**3.82 (0.36)**	**4.53 (0.37)**
F4	1993 – 2015	**107.86 (5.53)**	**-1.06 (2.00)**	**5.71 (0.30)**	**2.76 (9.30)**
F9	1993 – 2015	**114.56 (12.20)**	-9	**5.75 (0.65)**	**2.52 (11.20)**
F10	1993 – 2015	**106.75 (3.64)**	-9	**4.70 (0.43)**	**3.56 (1.95)**
F15	1993 – 2015	**103.20 (10.72)**	**0.04 (1.35)**	**6.03 (0.57)**	**0.21 (86.90)**
F18	1993 – 2015	**92.11 (1.34)**	-9	**4.13 (0.29)**	**2.32 (0.90)**
F19	1993 – 2004	**102.05 (26.5)**	**-0.53 (5.84)**	**6.18 (1.42)**	**1.52 (72.49)**
	2005 – 2015	**99.24 (9.22)**	**-6.72 (43.01)**	**5.96 (0.57)**	**6.25 (6.32)**
F20	1993 – 2004	**126.93 (16.72)**	**-1.69 (123.5)**	**5.58 (0.71)**	**4.26 (109.76)**
	2005 – 2015	**131.29 (22.94)**	**-2.2 (149.05)**	**5.86 (0.8)**	**4.17 (106.2)**
F21	1993 – 2015	**90.79 (2.63)**	**0.98 (18.72)**	**5.34 (0.23)**	**4.11 110.41)**
Size selectivity (3–knot spline)					
Fishery	Years (knot locations in cm)	Gradient Low	Gradient High	Value at 2nd knot	Value at 3rd knot
F1	1993 – 2015 (60, 90, 130)	**1.25 (0.29)**	**-1.48 (1.13)**	**8.02 (1.79)**	**-6.01 (11.85)**
F3	1993 – 2015 (70, 95, 120)	**0.68 (0.24)**	**-0.53 (0.35)**	**4.72 (1.21)**	**3.84 (2.15)**
F13	1993 – 2015 (60, 90, 140)	**0.17 (0.29)**	**-1.08 (1.05)**	**6.45 (6.59)**	**-2.66 (18.17)**

Table 4.3. Selectivity parameters used in the base case model for fisheries with selectivity assumed to be a product of size and age selectivity. Estimated parameters are shown in bold, with estimated standard deviation in parentheses. Size selectivity was assumed to follow a double-normal function. The optional initial and final parameters for all double-normal selectivity curves were fixed at -999 and ignored by the model. Age selectivity was modeled as estimated free parameters for ages-1 to 5, with all other ages fixed at a negligible low value (-9). Estimated age selectivity parameters at the lower (-9) or upper (9) bound were fixed at the bound on the final run to improve model optimization.

Size selectivity (double-normal)					
Fishery	Years	Parm 1 – Size at peak	Parm 2 – Plateau width	Parm 3 – Ascending slope	Parm 4 – Descending slope
F16	1993 – 2015	**70.90 (2.66)**	-9	**4.44 (0.28)**	**4.47 (0.39)**
F17	1993 – 2015	**74.32 (3.91)**	-9	**5.00 (0.25)**	**4.09 (0.62)**
F27	1993 – 2015	**60.34 (4.32)**	**-2.54 (2.13)**	**2.97 (0.97)**	**6.83 (1.90)**

Age selectivity (free parameters for ages-1 to 5)					
		Age-1	Age-2	Age-3	Age-4	Age-5
F16	1993 – 2015	**3.95 (0.71)**	**-7.96 (0.78)**	-9	**-4.92 (1.28)**	**-3.66 (5.99)**
F17	1993 – 2015	**0.38 (1.74)**	**-2.36 (0.50)**	**-3.03 (0.39)**	**-1.60 (1.09)**	9
F27	1993 – 1998	**0.90 (3.82)**	**-7.03 (5.15)**	**-7.36 (4.19)**	**-6.52 (9.50)**	-9
	1999 – 2015	**-1.51 (1.69)**	**0.28 (0.77)**	9	**7.50 (30.74)**	**-0.43 (3.21)**

Table 4.4. Fisheries without an estimated selectivity were assumed to have size selectivity identical to other fisheries (mirrored selectivity).

Mirrored selectivity			
Fishery without estimated selectivity	Mirrored to	Fishery without estimated selectivity	Mirrored to
F5	F1	F22	F13
F6	F2	F23	F13
F7	F3	F24	F21
F8	F4	F25	F13
F11	F9	F26	F21
F12	F10	F28	F16
F14	F13	F29	F16

Table 4.5. Sensitivity analyses conducted on the 2017 base case model for north Pacific albacore.

Sensitivity run number	Sensitivity run name	Description
Sensitivity to biological assumptions		
01	Natural mortality	Use a constant M of 0.3 y^{-1} for both sexes and all ages (same as 2014 assessment); and a constant M of 0.48 and 0.39 y^{-1} for female and male albacore of all ages, respectively
02	Stock-recruitment steepness	Use alternative values for the steepness parameter (h = 0.75; 0.80; and 0.85)
03	Growth	CV of L_{inf} is fixed at higher (0.06 & 0.08) levels. Lower CV levels were not investigated because CV values smaller than the base case model (0.04) was considered unreasonable
Sensitivity to data inputs		
04	Start year	Start year of the model is changed to 1966 (same as 2014 assessment). However, only the adult index from the Japanese longline fishery in Area 2 in Quarter 1 (F9) is fit. Size composition data from 1966 – 1992 are not fit. Selectivity for all fisheries prior to 1993 are assumed to be the same as in 1993.
05	Juvenile index	Fit to the Japan pole-and-line index for F17
06	Size composition weighting	Change the relative weighting of size composition data for all fisheries. Either down-weight size composition data of all fisheries (all lambda = 0.1) or fit size composition data for all fisheries at natural weight (all lambda = 1.0)
Sensitivity to model structure assumptions		
07	US longline asymptotic selectivity	Assume that the US longline fishery in Areas 2 & 4 (F20) has an asymptotic size selectivity
08	Equilibrium catch	Initial conditions: fit to equilibrium catch of each fishery estimated as the average of 10 years of annual catch during 1983 – 1992. Equilibrium catch of fisheries that were ≤50 t or ≤25,000 fish were assumed to be negligible.
09	2014 base case model structure	Model structure follows the 2014 assessment as close as possible (start year=1966; M=0.3 y^{-1} for both sexes; down-weight all size composition data; fit to Japan pole-and-line indices)

Table 5.1. Analytical estimates of catchability, mean input variance, variance adjustment, and model fit (root-mean-square-error; RMSE of predictions to observations) for the S1 abundance index in the 2017 base case model.

Index	Years	Catchability	Mean input CV	Variance adjustment	Input CV + Var. Adj.	RMSE
S1	1996 – 2015	5.399E-03	0.0981	0.1019	0.2000	0.1643

Table 5.2. Mean input variances (input N after variance adjustment) and model estimated mean variance (*effN*) of the size composition data components. Harmonic means of *effN* and ratio of input N to *effN* are also provided. A higher *effN* indicates a better model fit. Number of observations corresponds to the number of quarters in which size composition data were sampled in a fishery. * indicate size composition data were down-weighted with a lambda of 0.1.

Fishery	Number of observations	Mean input N after var. adj.	Mean effective N (effN)	Harmonic mean of effN	Harmonic mean effN / mean input N
F1	23	7.2	61.8	31.0	4.3
F2	21	7.2	51.8	36.3	5.0
F3	14	7.2	38.8	22.8	3.2
F4	23	7.2	144.7	75.9	10.6
F9*	23	7.2	84.6	61.0	8.5
F10*	54	7.2	119.9	41.9	5.8
F13*	48	7.2	76.7	25.1	3.5
F15	8	7.2	43.9	25.1	3.5
F16	26	7.0	40.4	23.1	3.3
F17	31	7.2	30.5	10.9	1.5
F18	9	6.9	15.1	10.2	1.5
F19*	46	6.5	31.6	14.9	2.3
F20*	78	7.8	72.2	29.2	3.7
F21	32	7.2	66.7	30.7	4.3
F27	34	7.2	168.1	90.6	12.6

Table 5.3. Total biomass (Q1, age-1+), female spawning biomass (Q2), limit reference point adopted by the NC of the WCPFC ($20\%SSB_{current, F=0}$), recruitment, and fishing intensity (1-SPR) estimated in the base case model. Estimated virgin biomass (SSB_0) and recruitment are 171,869 t and 226 million fish, respectively.

Year	Total biomass age-1+ (t)	Female spawning biomass (t)	Limit reference point ($20\%SSB_{current, F=0}$) (t)	Recruitment (x1000 fish)	Fishing intensity (1-SPR)
1993	1,177,870	85,372	35,663	275,070	0.28
1994	1,207,150	123,061	40,462	137,073	0.34
1995	1,158,510	139,481	42,352	201,144	0.33
1996	1,091,700	136,691	40,651	221,971	0.40
1997	1,035,960	126,332	38,923	197,482	0.48
1998	974,247	117,607	38,751	135,316	0.48
1999	903,182	102,724	36,009	307,587	0.61
2000	868,379	83,724	32,882	214,353	0.47
2001	907,988	81,353	32,704	202,717	0.50
2002	915,714	77,910	32,406	174,992	0.58
2003	880,809	69,428	29,929	207,260	0.51
2004	854,827	78,076	31,912	279,233	0.53
2005	879,307	83,424	34,429	194,316	0.41
2006	927,161	82,736	33,873	154,586	0.42
2007	920,871	80,477	32,380	155,554	0.52
2008	858,256	78,362	31,702	233,597	0.39
2009	856,764	90,103	34,060	225,286	0.49
2010	870,168	91,015	34,781	213,096	0.45
2011	899,259	81,575	32,224	173,259	0.50
2012	894,577	72,981	29,560	126,232	0.51
2013	831,636	74,762	30,044	206,697	0.49
2014	796,877	80,770	31,875	230,470	0.51
2015	805,840	80,618	32,614	219,332	0.47

Table 5.4. Estimates of maximum sustainable yield (MSY), female spawning biomass (SSB) quantities, and fishing intensity (F) based reference point ratios for north Pacific albacore tuna for the base case assessment and important sensitivity analyses. SSB_0 and SSB_{MSY} are the unfished biomass of mature female fish and at MSY, respectively. The Fs in this table are not based on instantaneous fishing mortality. Instead, the Fs are indicators of fishing intensity based on SPR and calculated as 1-SPR so that the Fs reflects changes in fishing mortality. SPR is the equilibrium SSB per recruit that would result from the current year's pattern and intensity of fishing mortality. Current fishing intensity is based on the average fishing intensity during 2012-2014 ($F_{2012-2014}$).

Quantity	Base Case	$M = 0.3 \ y^{-1}$	Growth CV = 0.06 for L_{inf}
MSY (t) [A]	132,072	92,027	118,836
SSB_{MSY} (t) [B]	24,770	42,098	22,351
SSB_0 (t) [B]	171,869	270,879	156,336
SSB_{2015} (t) [B]	80,618	68,169	63,719
$SSB_{2015}/20\%SSB_{current, F=0}$ [B]	2.47	1.31	2.15
$F_{2012-2014}$	0.51	0.74	0.57
$F_{2012-2014}/F_{MSY}$	0.61	0.89	0.68
$F_{2012-2014}/F_{0.1}$	0.58	0.90	0.65
$F_{2012-2014}/F_{10\%}$	0.56	0.81	0.63
$F_{2012-2014}/F_{20\%}$	0.63	0.91	0.71
$F_{2012-2014}/F_{30\%}$	0.72	1.04	0.81
$F_{2012-2014}/F_{40\%}$	0.85	1.21	0.96
$F_{2012-2014}/F_{50\%}$	1.01	1.47	1.16

A – MSY includes male and female juvenile and adult fish
B – Spawning stock biomass (SSB) in this assessment refers to mature female biomass only.

FIGURES

Figure 2.1. Total annual reported catch of north Pacific albacore (*Thunnus alalunga*) by ISC member and non-member countries, 1952-2015. Non-ISC member countries are grouped in the Other category and may include catches from Tonga, Belize, Cook Islands, Ecuador, Vanuatu, and Vietnam.
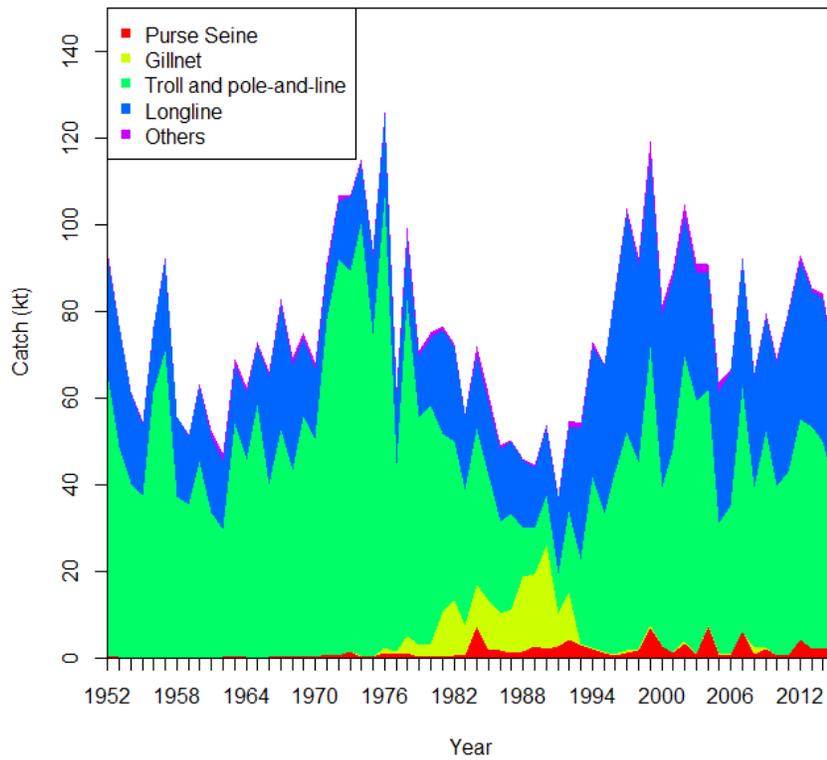
Figure 2.2. Total annual reported catch of north Pacific albacore by major gear types, 1952-2015. The Other Gears category includes set nets, recreational, hand line, and harpoon.
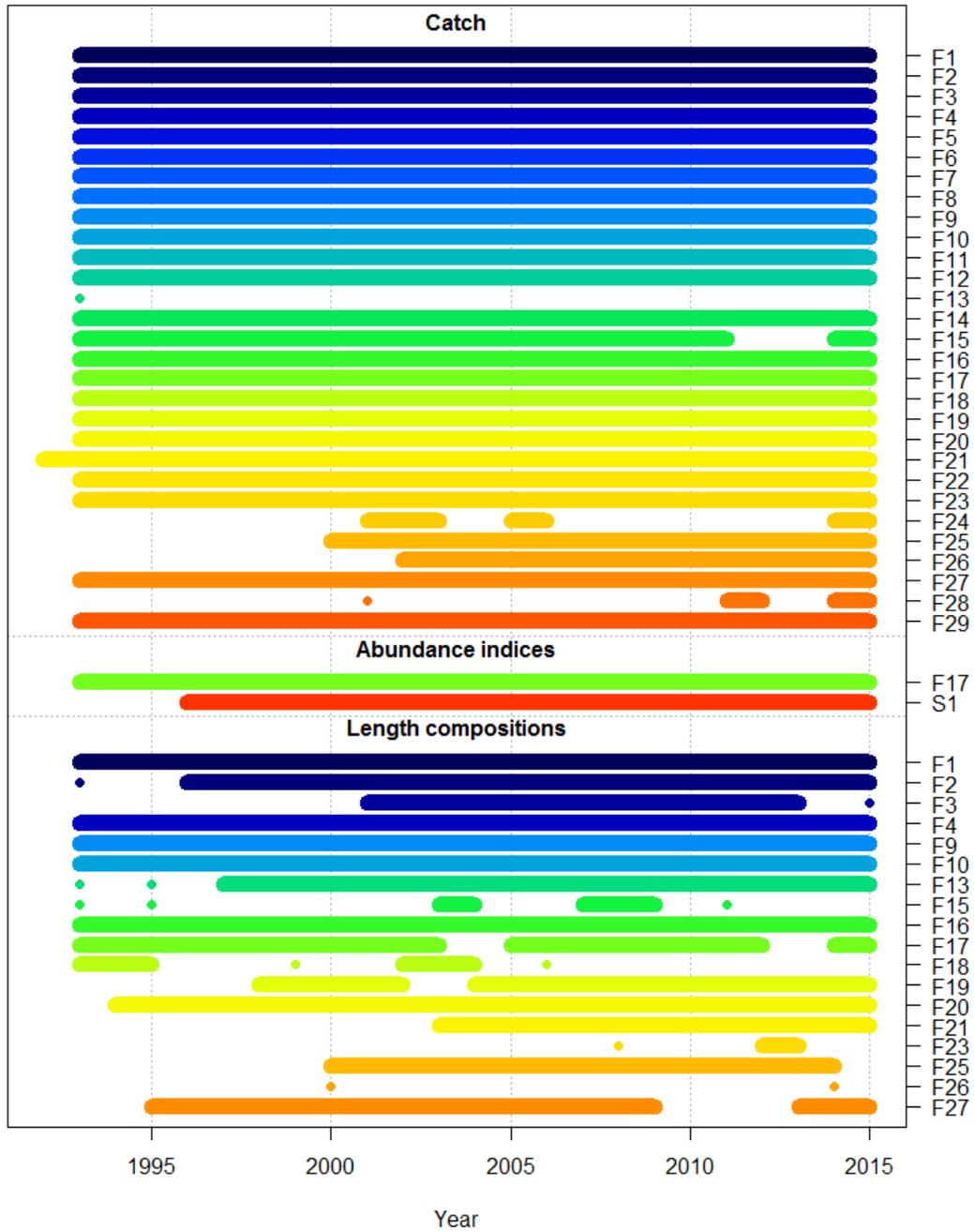
Figure 3.1. Temporal coverage and sources of catch, abundance indices, and length composition data by fishery used in the 2017 assessment of north Pacific albacore tuna. See the text and Table 3.1 for detailed descriptions of fishery codes.
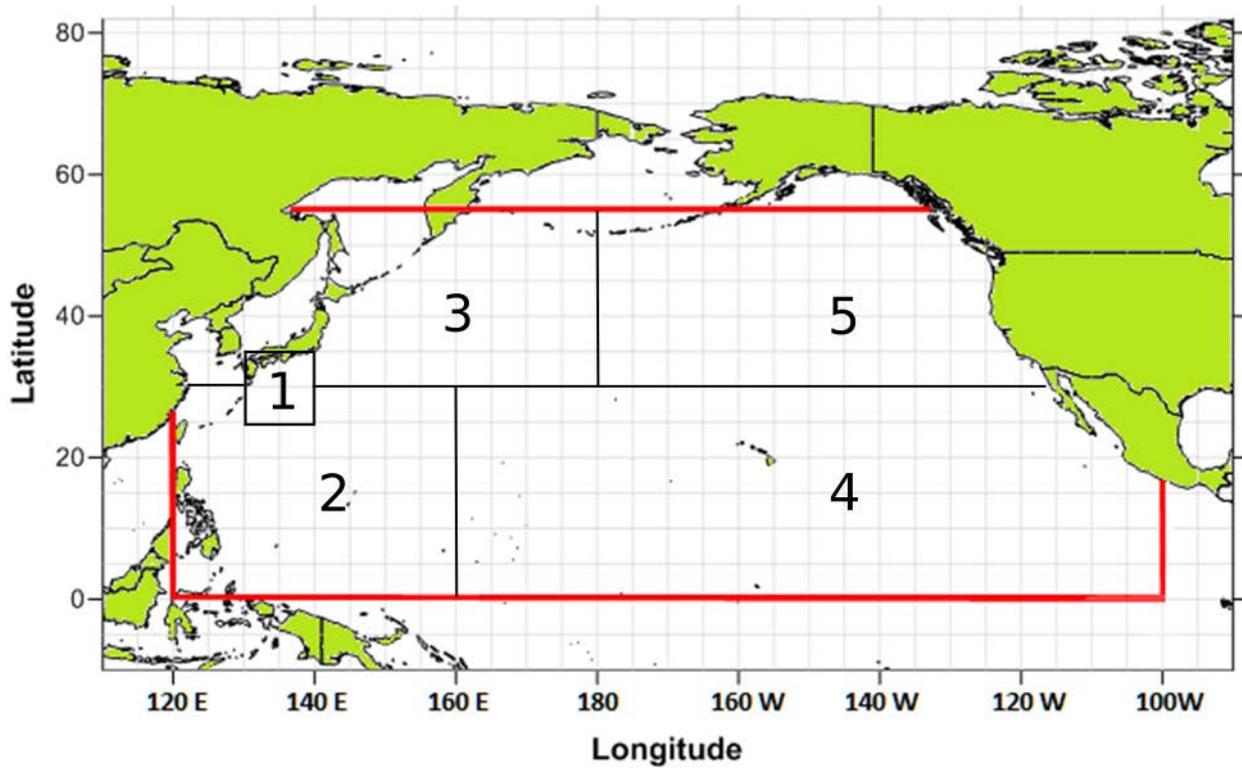
Figure 3.2. Spatial domain (red box) of the north Pacific albacore stock (*Thunnus alalunga*) in the 2017 stock assessment. Fishery definitions were based on five fishing areas (black boxes and numbers) defined from cluster analyses of size composition data.
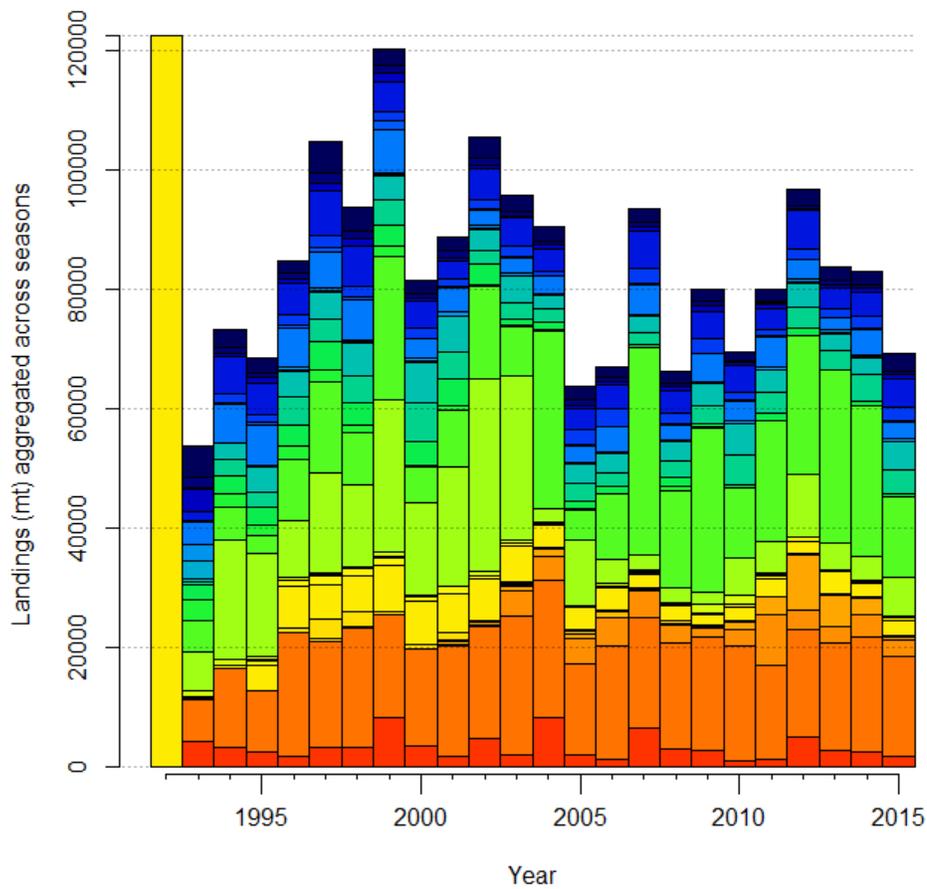
Figure 3.3. Catch (t) by fishery in the base case model. Color indicates fishery in base case model (Table 3.1) with F1 in dark blue and F29 in dark red. Catch in weight for some fisheries was estimated from catch in numbers. First bar (yellow) indicates the estimated initial catch of F21.
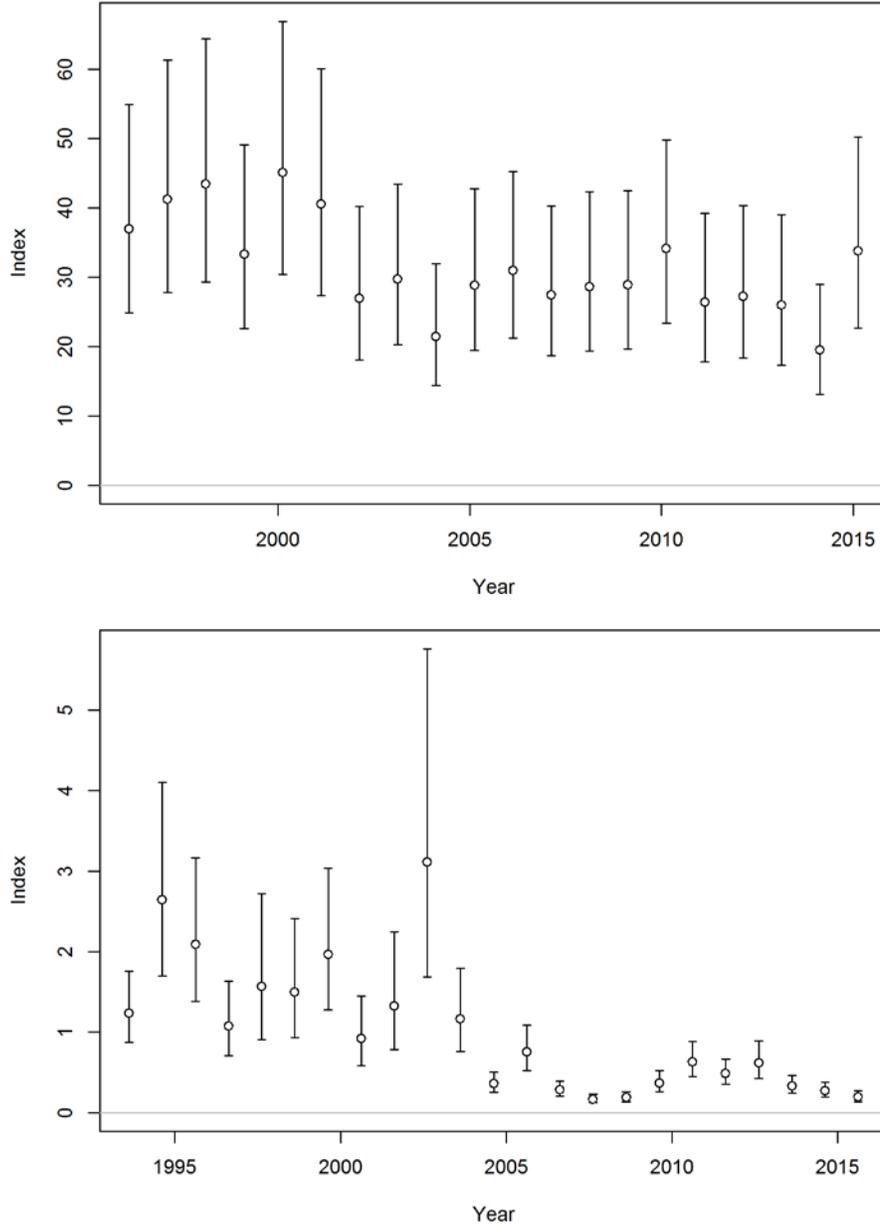
Figure 3.4. Trends and coefficients of variation (CVs; input + additional CVs) of the primary adult index (S1; upper panel) used in the base case model and the juvenile index (Japanese pole-and-line; F17; lower panel) used in sensitivity model runs. See Table 3.2 for index values and input CVs.
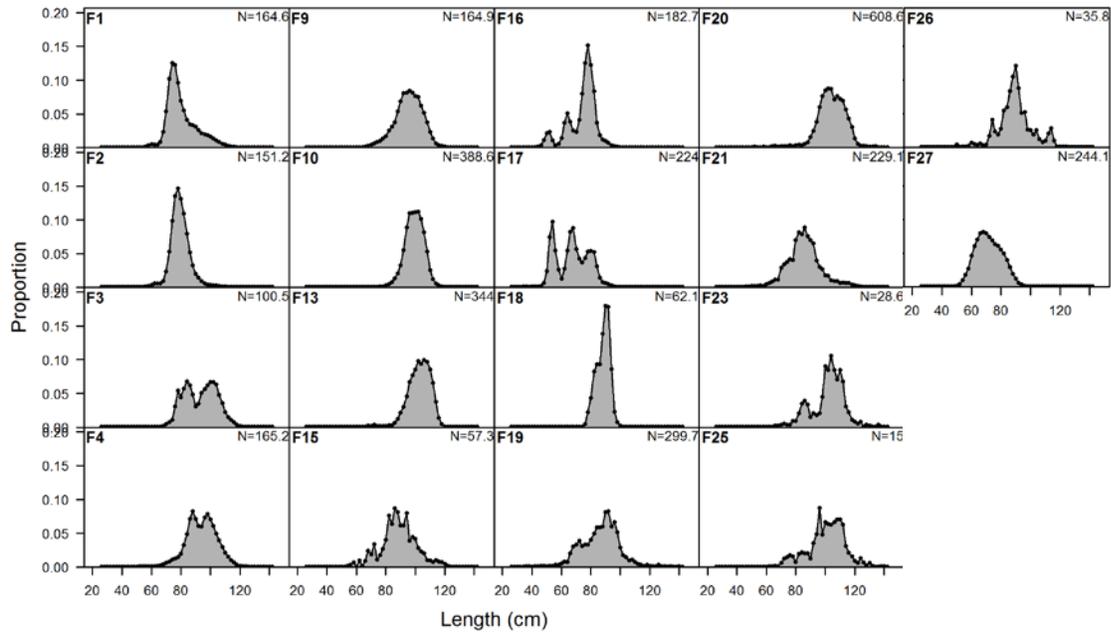
Figure 3.5. Aggregated size composition data in the base case model for the 2017 north Pacific albacore stock assessment. Note that size composition data for F23, F25, and F26 were not fitted in the base case model. See Table 3.1 for description of fisheries.
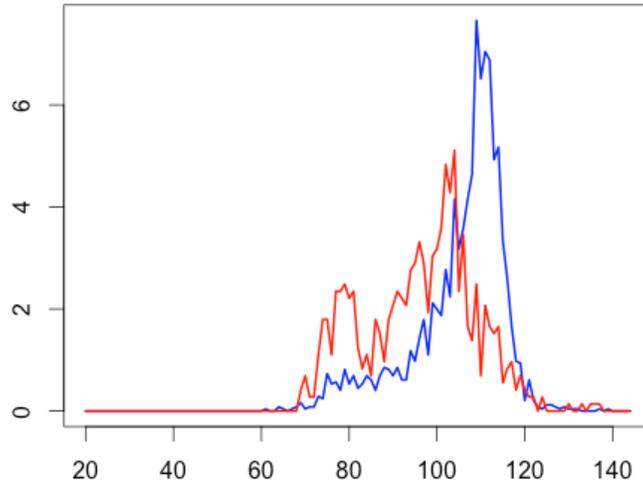
Figure 3.6. Proportion of males and females by length (fork length in cm) sampled in Japanese research and training vessel longline catches from 1987 to the present. Data are aggregated across years and fishing areas. Sex composition data are not fitted in the base case model.
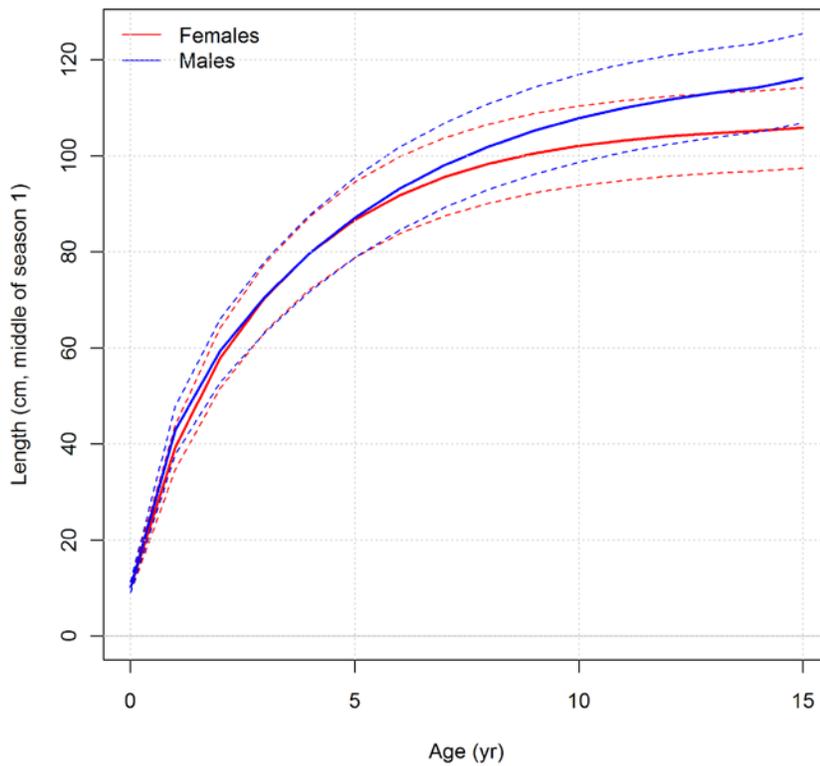
Figure 4.1. Growth model of north Pacific albacore used in the 2017 assessment. Dashed lines indicate 95% confidence intervals. Based on sex-specific growth model by Xu et al. (2014). See Table 4.1 for detailed parameters.
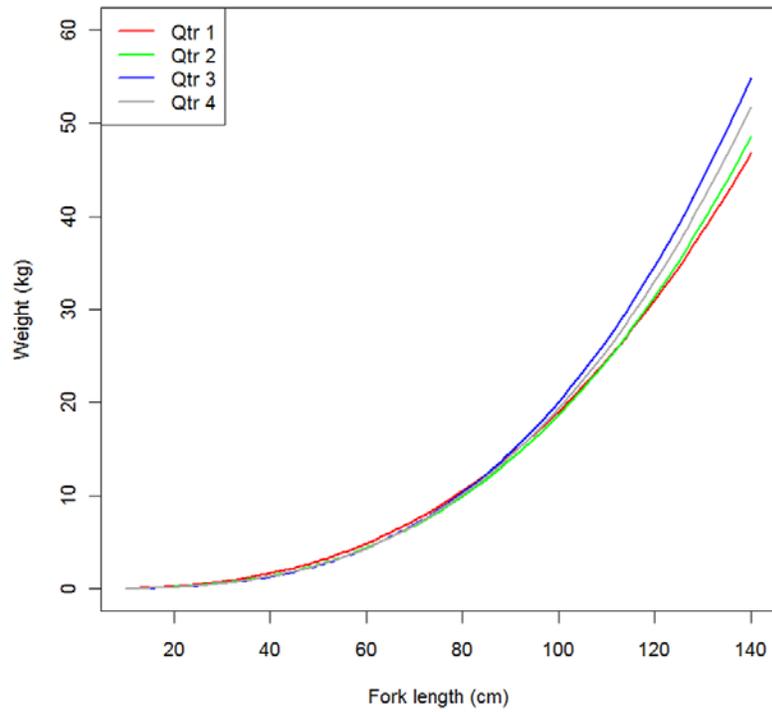
Figure 4.2. Seasonal weight-at-length relationships of north Pacific albacore used in the 2017 assessment. Based on Watanabe et al. (2006). Male and female weight-at-length relationships were assumed to be identical. See Table 4.1 for detailed parameters.
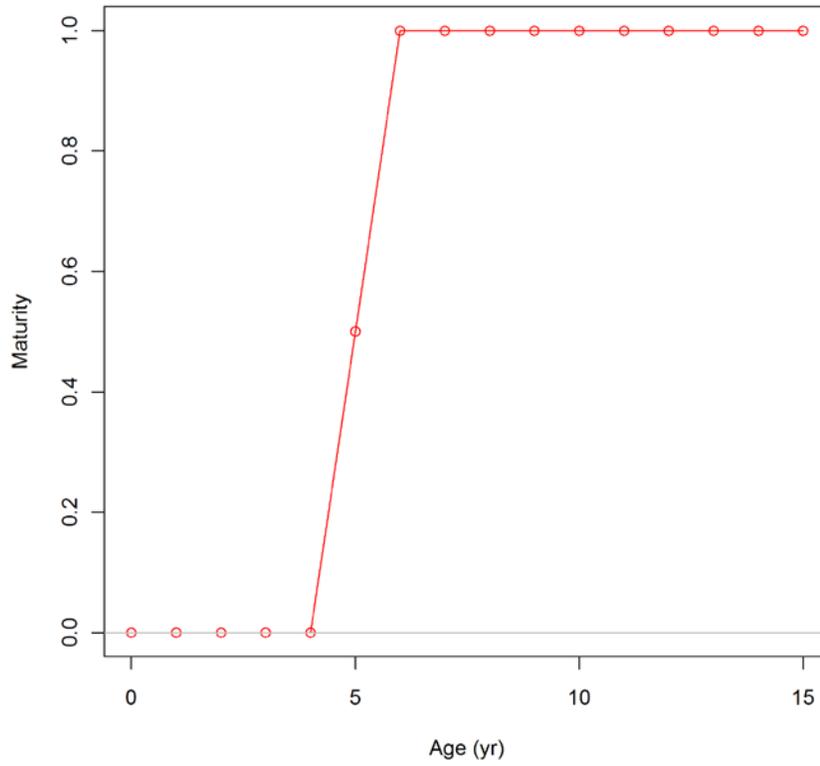
Figure 4.3. Maturity-at-age for female north Pacific albacore used in the 2017 assessment. See Table 4.1 for detailed parameters.
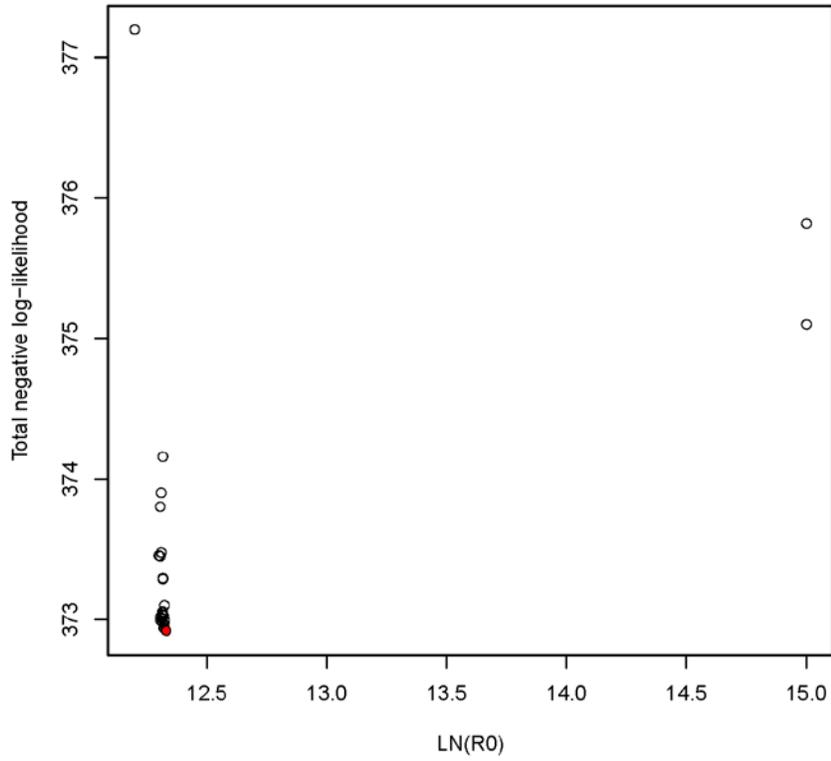
Figure 5.1. Total negative log-likelihood and estimated virgin recruitment in log-scale [ln(R_0)] from 50 model runs with different phasing and initial values of ln(R_0) and other important parameters, as well as randomly jittered initial values for all estimated parameters in the base-case model. Red closed circle shows results from the model run using initial parameters and phasing corresponding to the 2017 base case model, which had the lowest total negative log-likelihood (-372.919) of all 50 model runs.
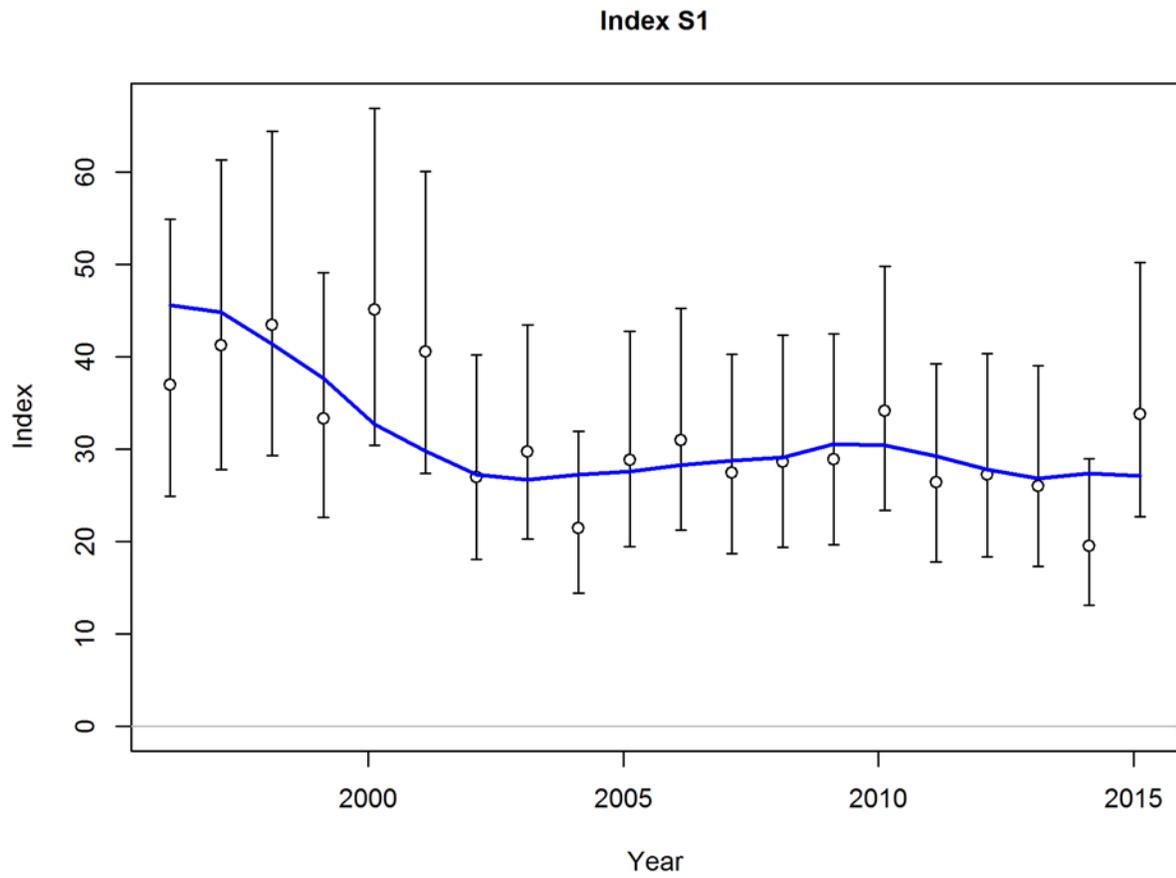
Figure 5.2. Observed (open circles) and predicted (blue line) relative abundance from the S1 adult abundance index in the 2017 base case model. Error bars are the 95% confidence intervals.
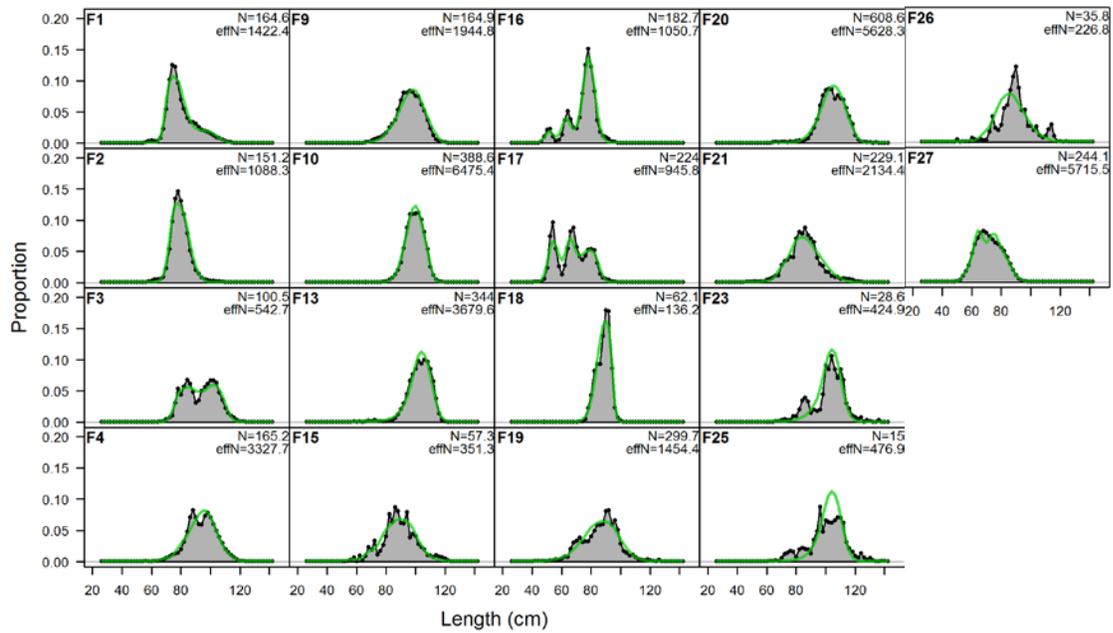
Figure 5.3. Observed (grey) and model predicted (green line) aggregated size compositions for fisheries in the 2017 base-case model. F23, F25, and F26 had size composition data available but were not fitted in the base case model because their size composition data were not raised to the catch. See Table 3.1 for description of fisheries.
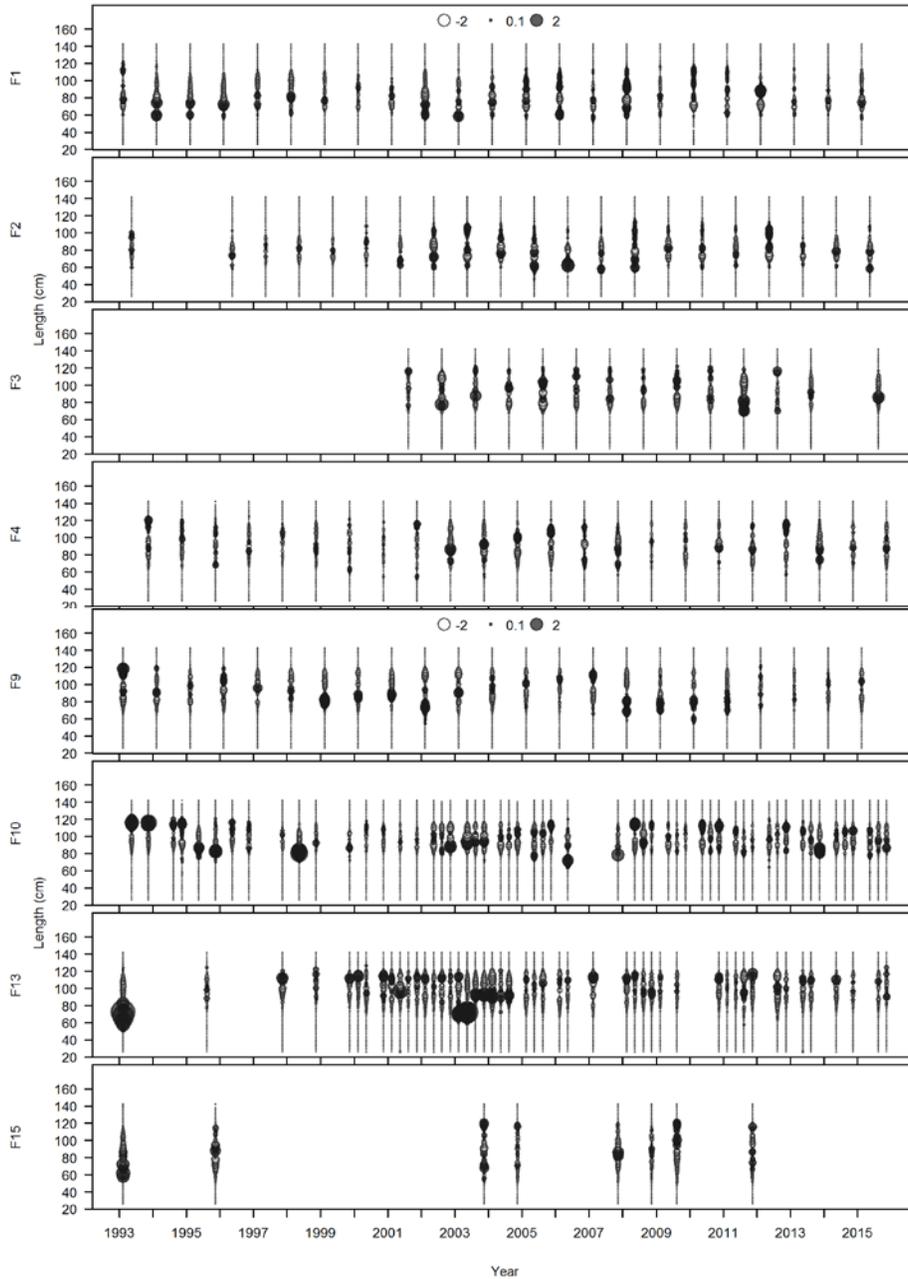
Figure 5.4. Pearson residuals of model fit to size composition data from fisheries in the 2017 base case model. Filled and open circles represent observations (i.e., proportions at size) that are larger and smaller than model predictions, respectively. Area of the circle is proportional to absolute values of residuals. Note that the size compositions of F23, F25, and F26 were not fitted in the base case model.
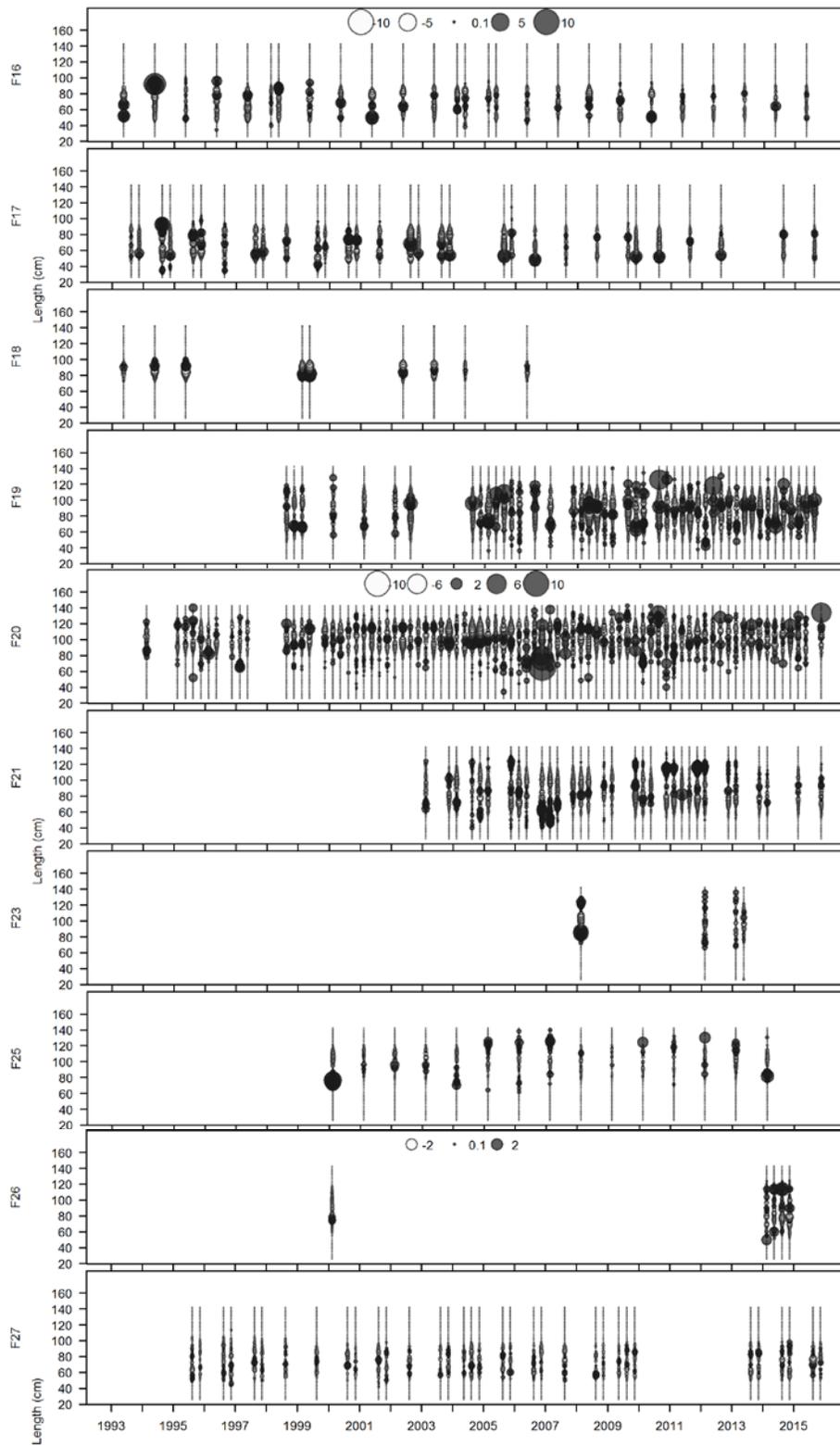
Figure 5.4. continued.
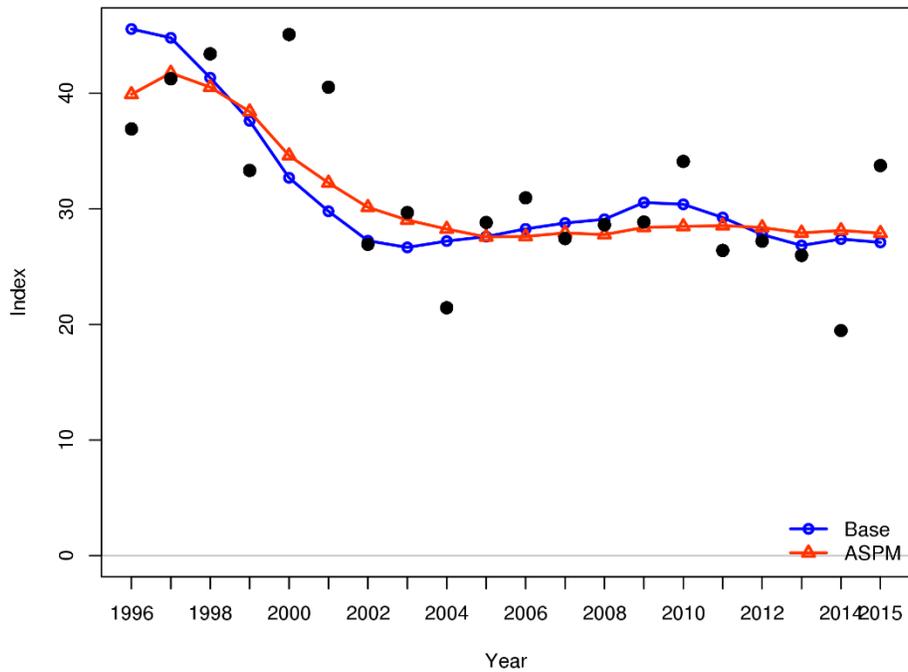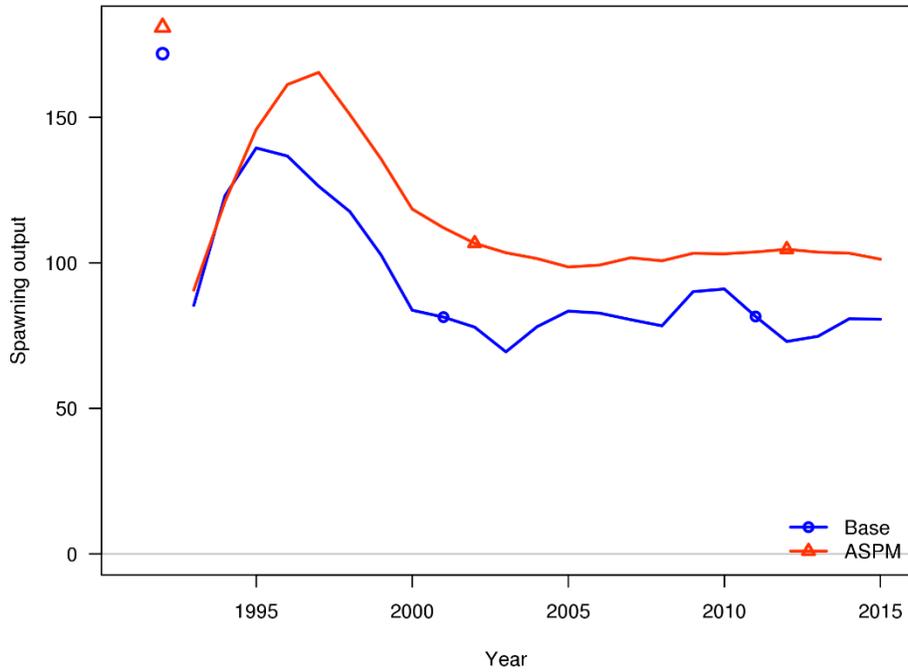
Figure 5.5. Estimated female spawning stock biomass (upper panel) and fit to the S1 adult abundance index (lower panel) of the age-structured production model (ASPM; red) and the base case model (blue). Black circles in the lower panel indicate observations of the S1 index.
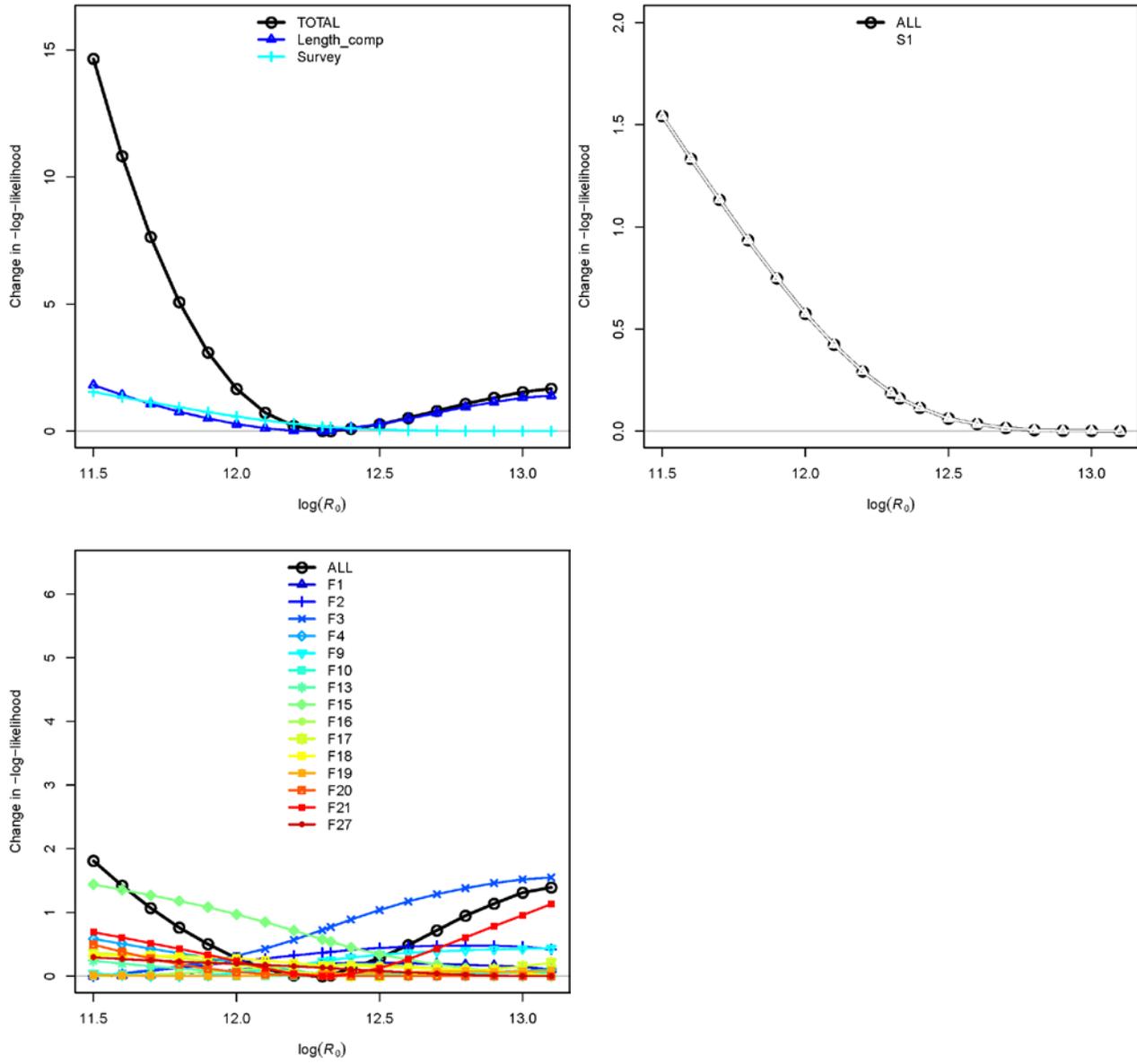
Figure 5.6. Likelihood profiles with respect to virgin recruitment [log(R_0)] of the main data components (upper left), S1 abundance index (upper right), and size compositions (lower left) of the 2017 base case model.
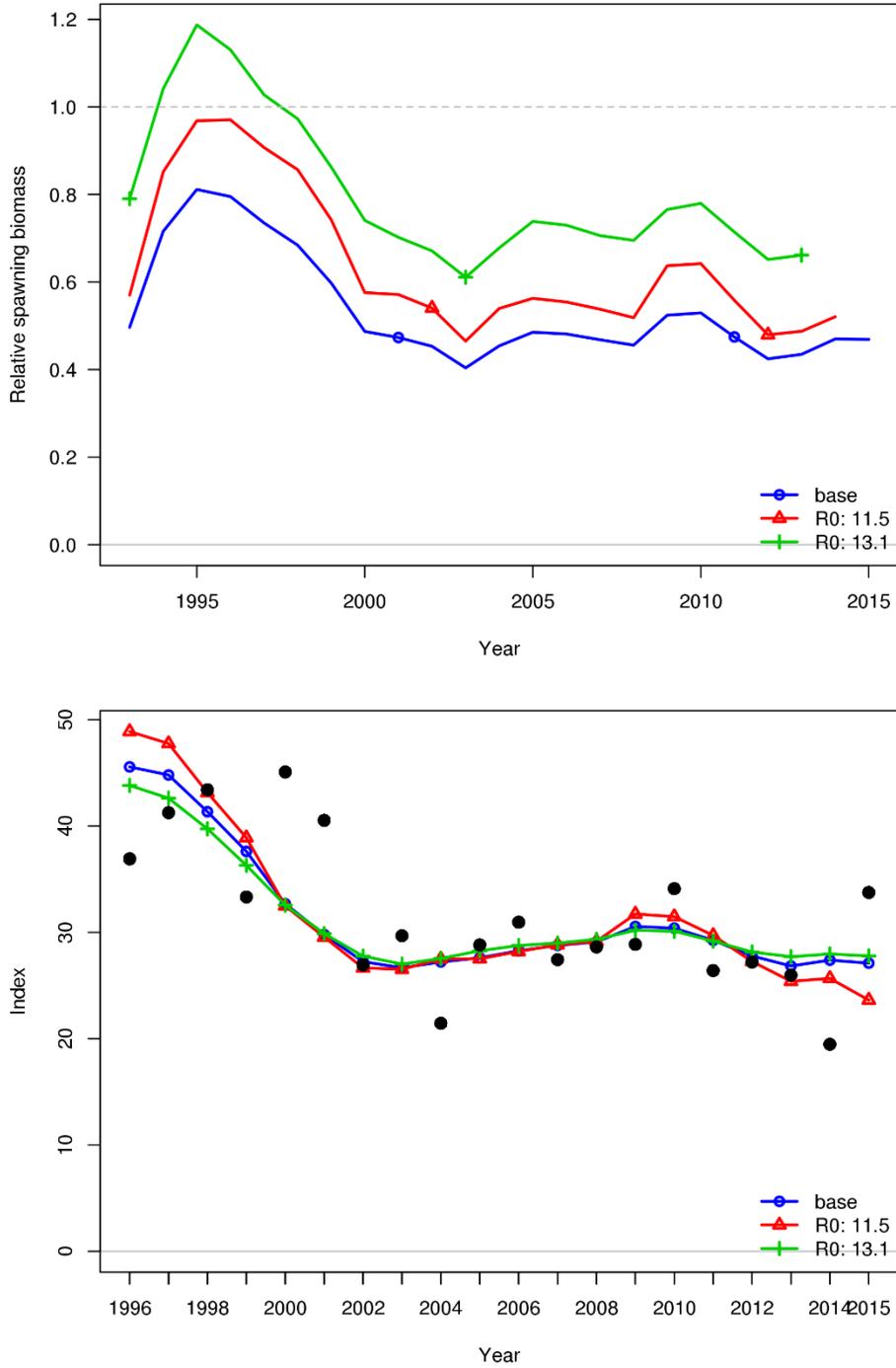
Figure 5.7. Estimated female spawning stock biomass (SSB) relative to virgin SSB (upper panel) and fit to the S1 adult abundance index (lower panel) of the base case model (blue) and models with virgin recruitment [log(R_0)] fixed at 11.5 (red) and 13.1 (green). Black circles in the lower panel indicate observations of the S1 index.
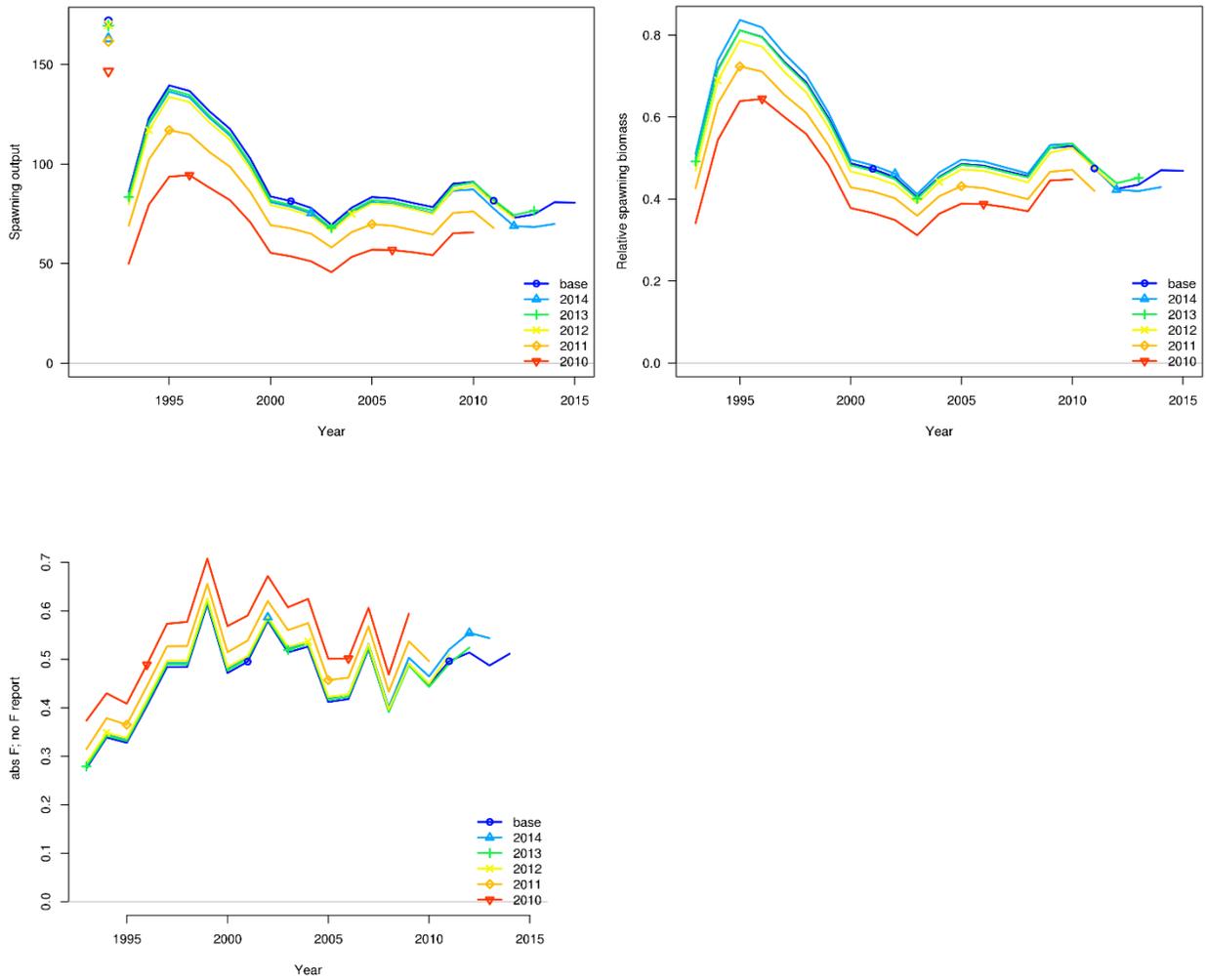
Figure 5.8. Estimated female spawning biomass (SSB) (upper left), relative SSB (upper right) and fishing intensity (1 – SPR) (lower right) of the base case model (blue) and models with one to five terminal years of data removed.
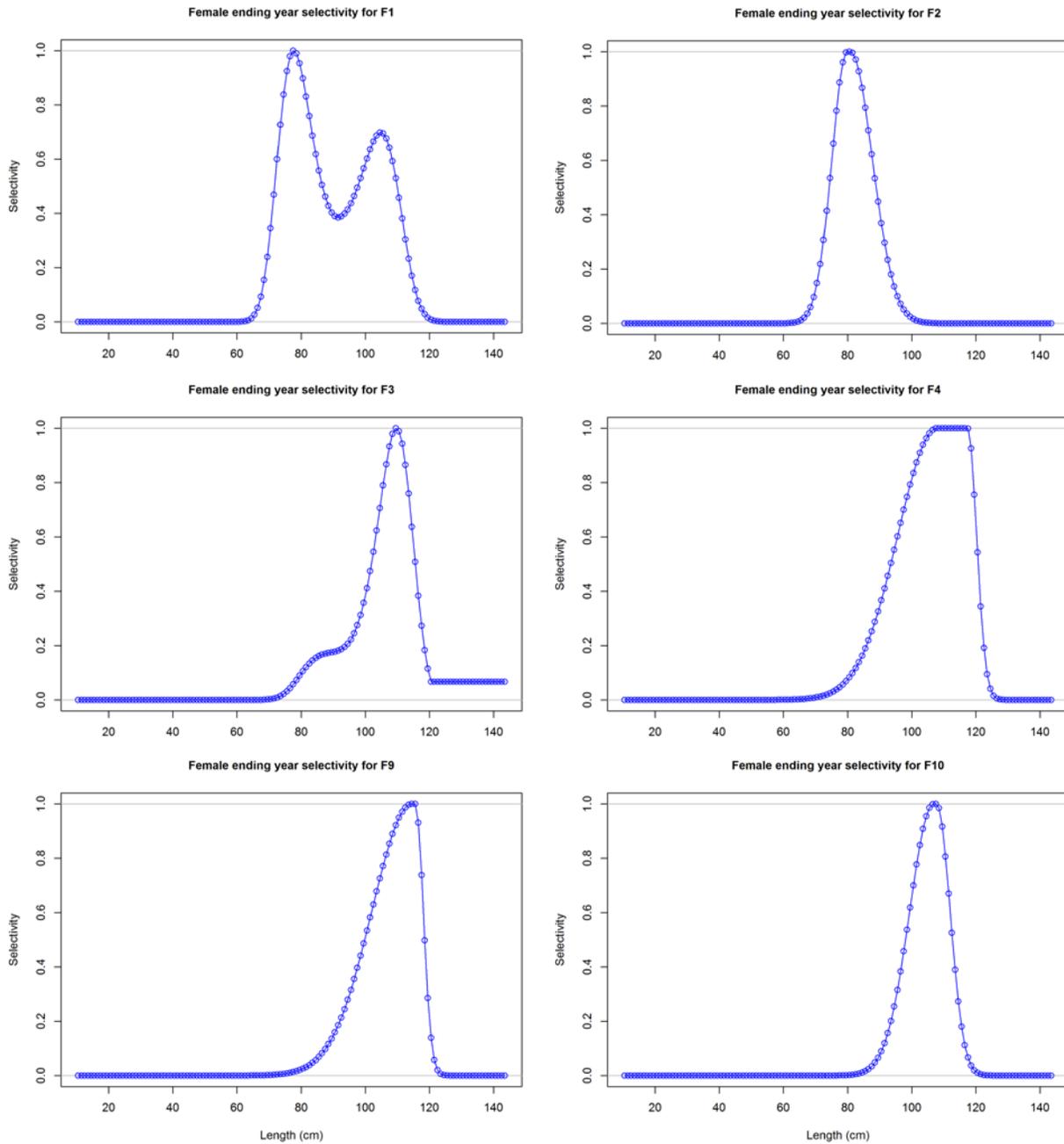
Figure 5.9. Estimated selectivity for fisheries with size-only selectivity in the 2017 base case model. Selectivity patterns displayed as 3-dimensional plots have time-varying selectivity. Male selectivity is identical to female selectivity in the base case model. Only fisheries with size composition data fitted in the model are shown.
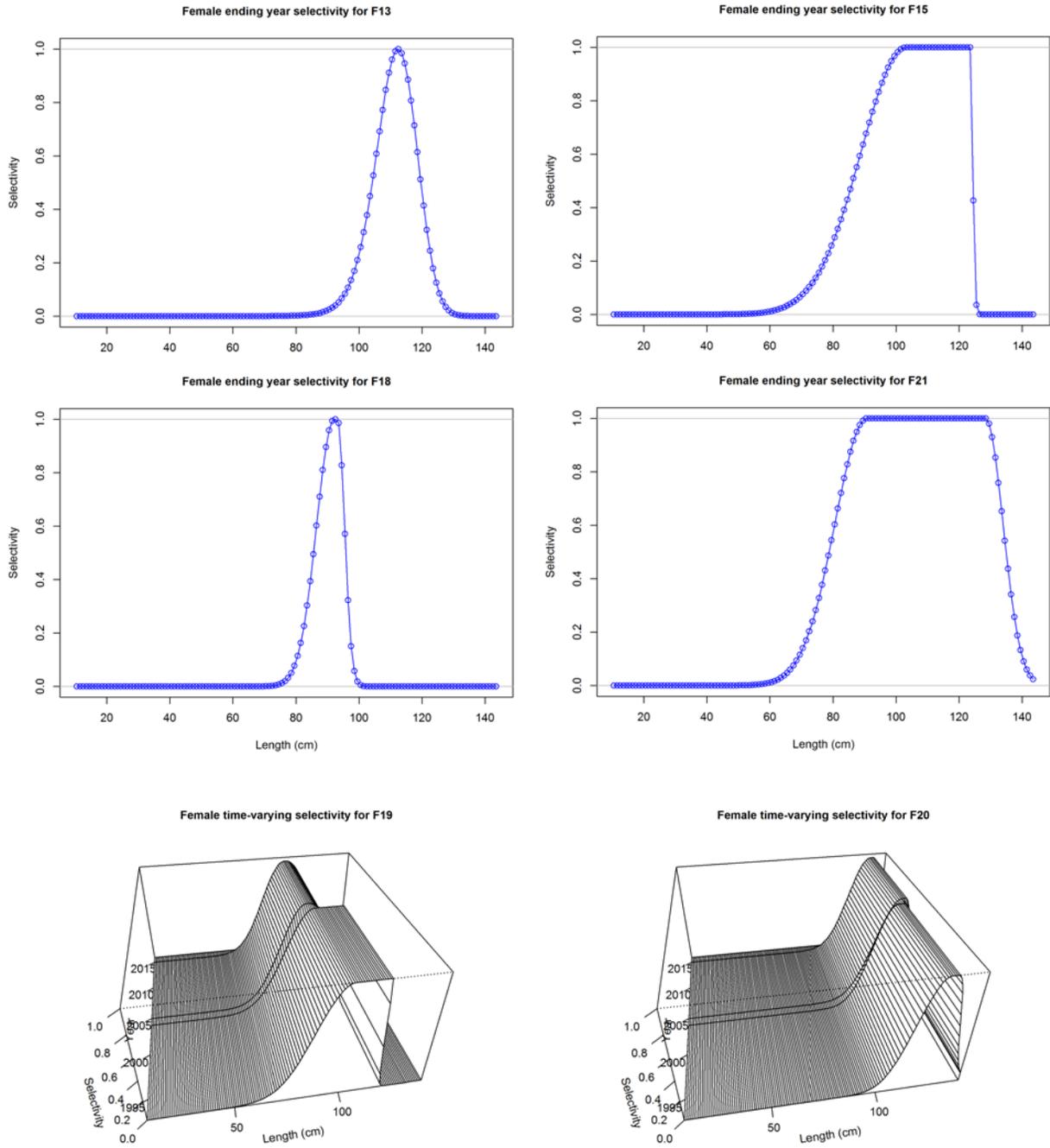
Figure 5.9. continued.
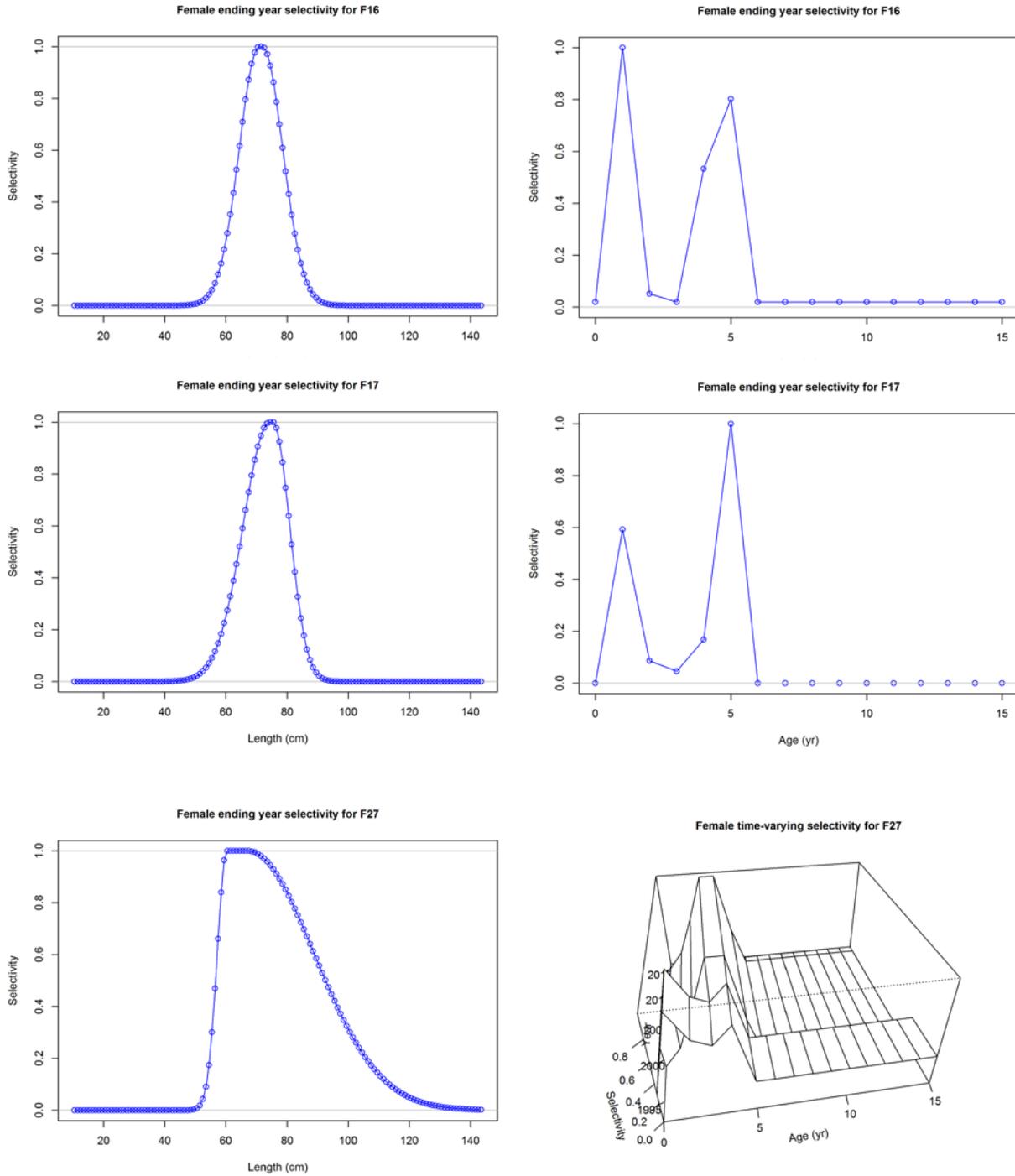
Figure 5.10. Estimated selectivity for fisheries with selectivity assumed to be a product of size (left) and age (right) selectivity, in the 2017 base case model. Selectivity patterns displayed as 3-dimensional plots have time-varying selectivity. Male selectivity is identical to female selectivity in the base case model. Only fisheries with size composition data fitted in the model are shown.

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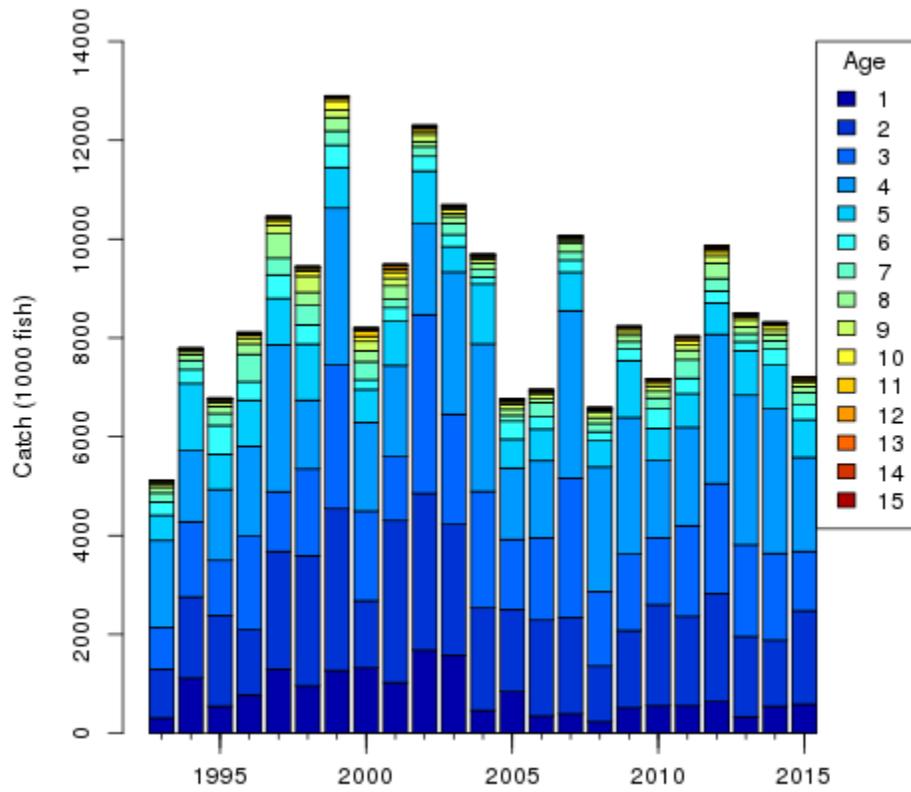
Figure 5.11. Historical catch-at-age of north Pacific albacore (*Thunnus alalunga*) estimated by the 2017 base case model.

Fraction female in numbers at age

Fraction female in numbers at length
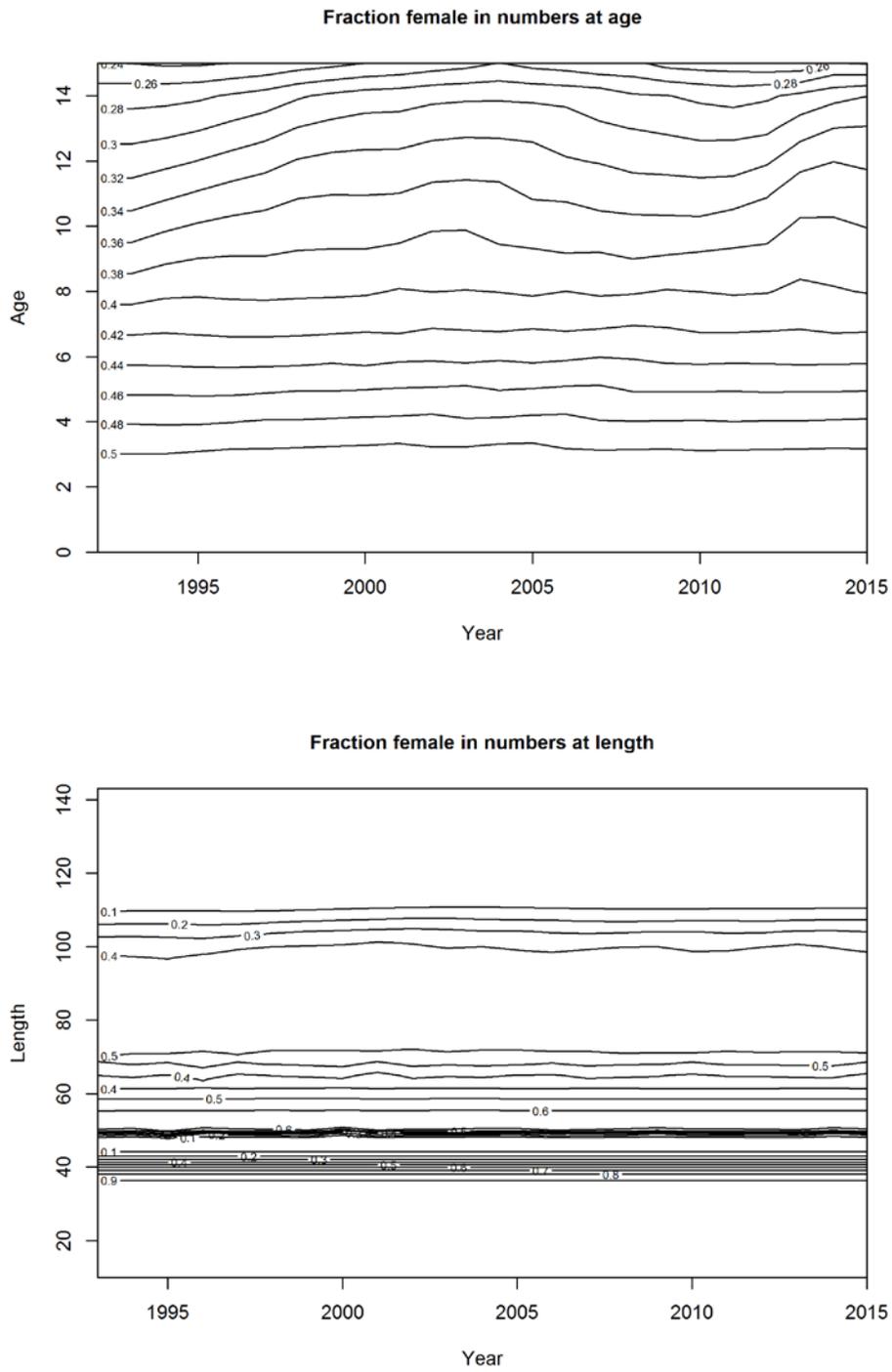
Figure 5.12. Fraction of females in the population by age (upper) and fork length in cm (lower) in the 2017 base case model.

A.

B.

C.
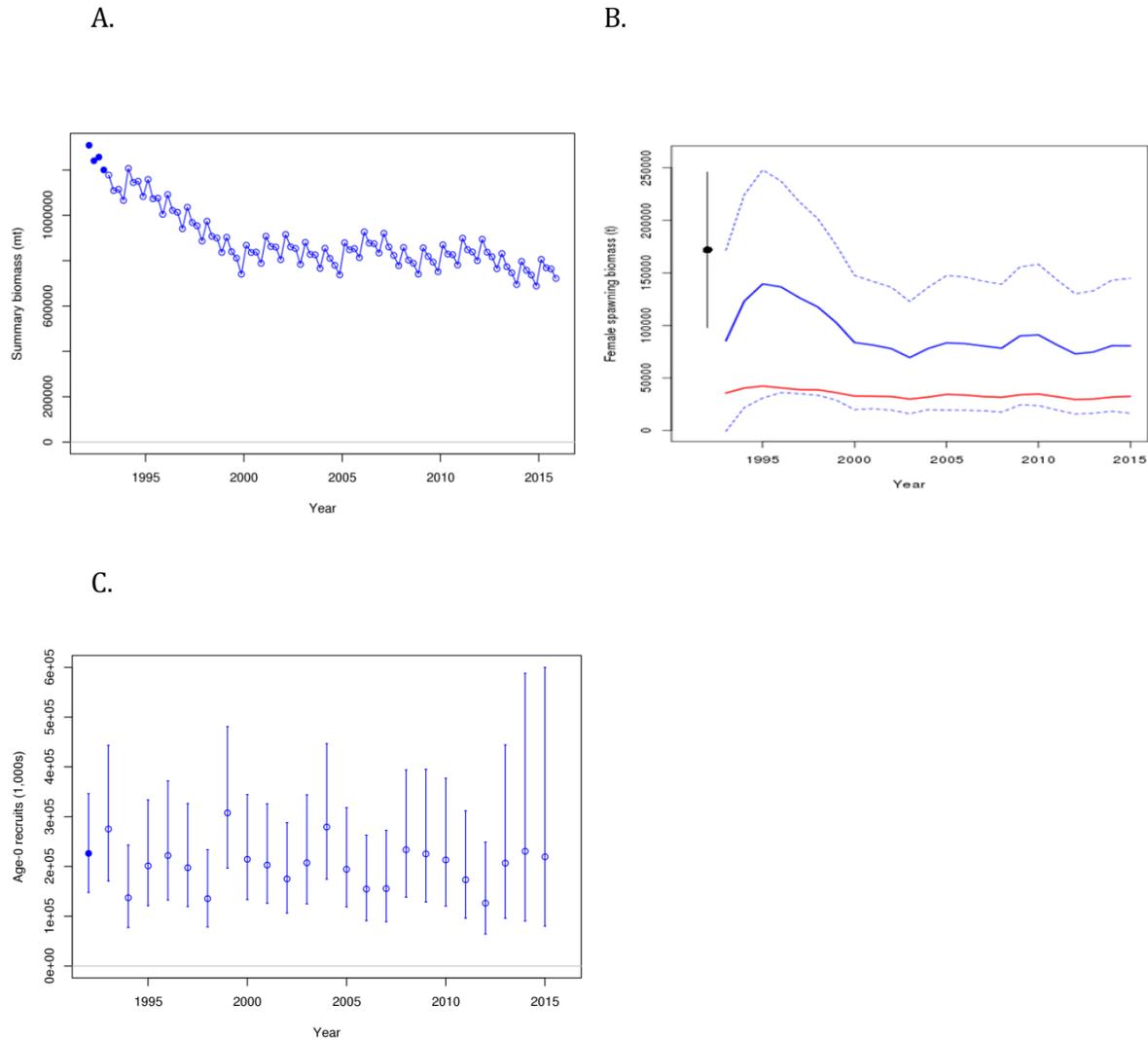
Figure 5.13. Maximum likelihood estimates of (A) total age-1+ biomass (open circles) (B), female spawning biomass (SSB) (solid blue line), and (C) age-0 recruitment (open circles) of north Pacific albacore tuna (*Thunnus alalunga*). Dashed lines (B) and vertical bars (C) indicate 95% confidence intervals of the female SSB and recruitment estimates respectively. Red line indicates the 20%$SSB_{current, F=0}$ limit reference point, which is based on dynamic SSB_0. Closed black circle and error bars in (B) are the maximum likelihood estimate and 95% confidence intervals of unfished female spawning biomass, SSB_0. Since the assessment model represents time on a quarterly basis, there are four estimates of total biomass (A) for each year, but only one annual estimate of female SSB (B) and recruitment (C).

Figure 5.14. Estimated sex-specific instantaneous fishing mortality-at-age (F-at-age) for the 2017 base case model, averaged across 2012-2014.
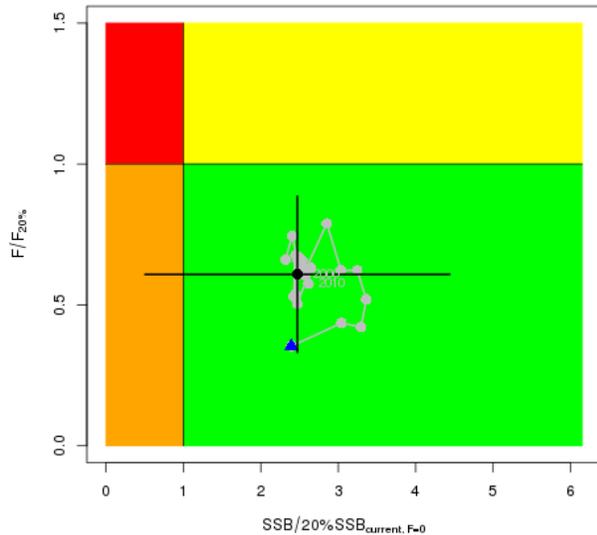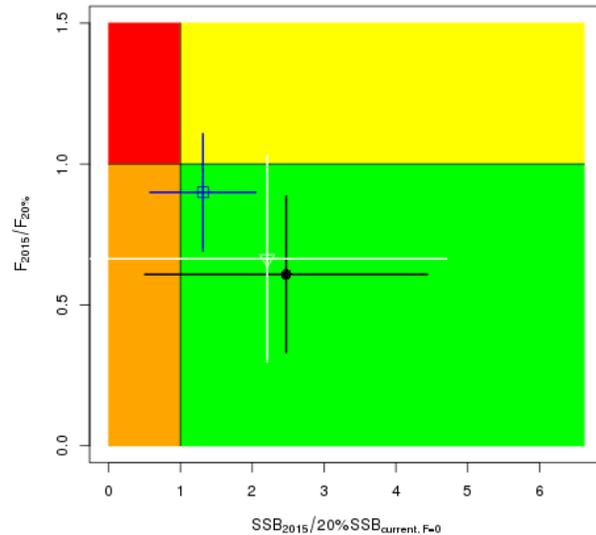
Figure 5.15. (**A**) Kobe plot showing the status of the north Pacific albacore (*Thunnus alalunga*) stock relative to the $20\%SSB_{current, F=0}$ biomass-based limit reference point, and equivalent fishing intensity ($F_{20\%}$; calculated as $1\text{-}SPR_{20\%}$) over the base case modeling period (1993-2015). Blue triangle indicates the start year (1993) and black circle with 95% confidence intervals indicates the terminal year (2015). (**B**) Kobe plot showing stock status and 95% confidence intervals in the terminal year (2015) of the base case model (black; closed circle) and important sensitivity runs with $M = 0.3$ y^{-1} for both sexes (blue; open square), and $CV = 0.06$ for L_{inf} in the growth model (white; open triangle). Fs in this figure are not based on instantaneous fishing mortality. Instead, the Fs are indicators of fishing intensity based on SPR and calculated as 1-SPR so that the Fs reflect changes in fishing mortality. SPR is the equilibrium SSB per recruit that would result from the current year's pattern and intensity of fishing mortality.
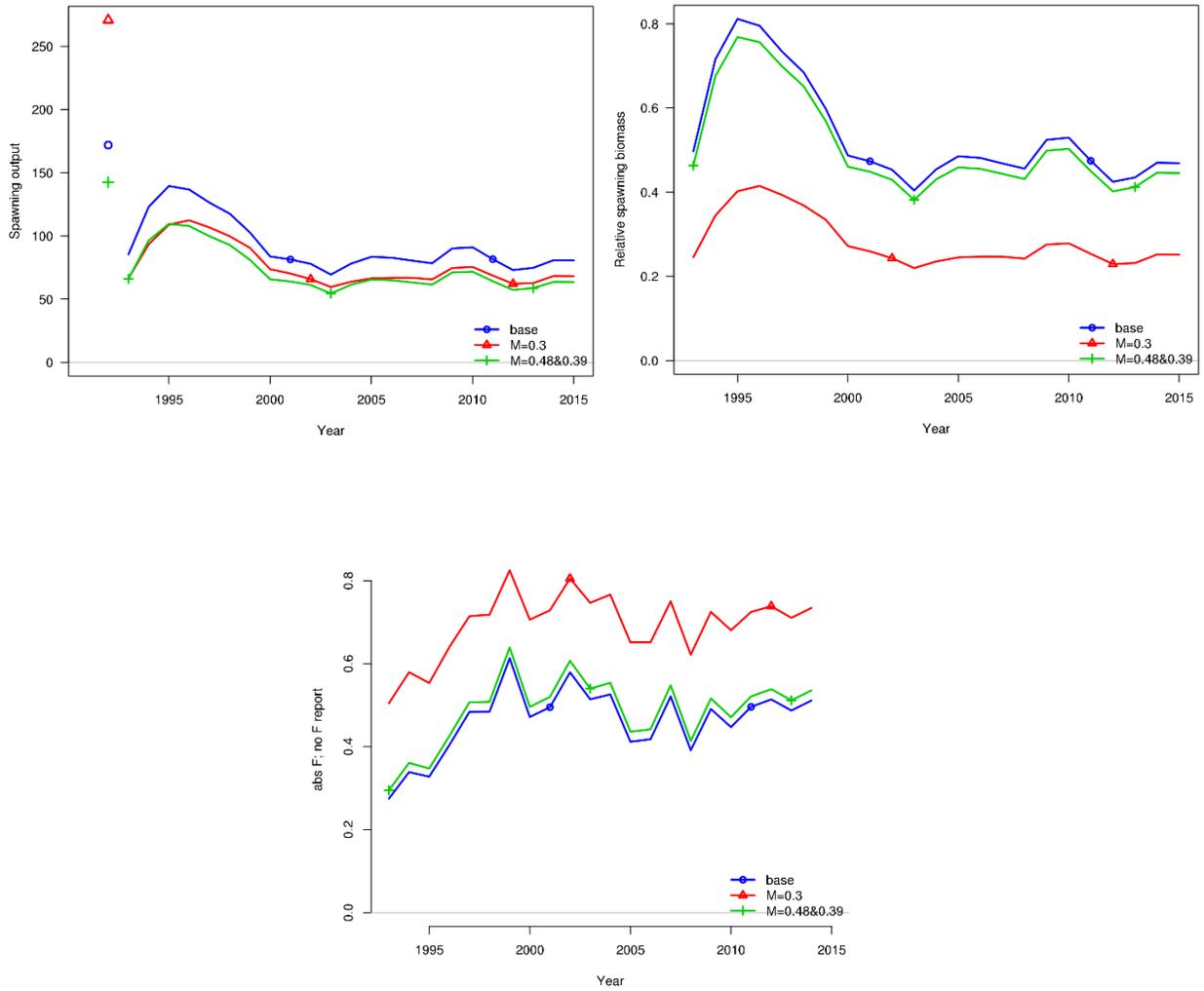
Figure 5.16. Estimated female spawning biomass (upper left), spawning biomass depletion (upper right), and fishing intensity (1-SPR) (lower) for the 2017 base case model (blue), and two sensitivity runs with alternative natural mortality schedules [constant M of 0.3 y⁻¹ for both sexes and all ages (red); constant M of 0.38 and 0.49 y⁻¹ for males and females, respectively, of all ages (green)]. See Table 4.5 and Section 5.6.1 for details on sensitivity runs.
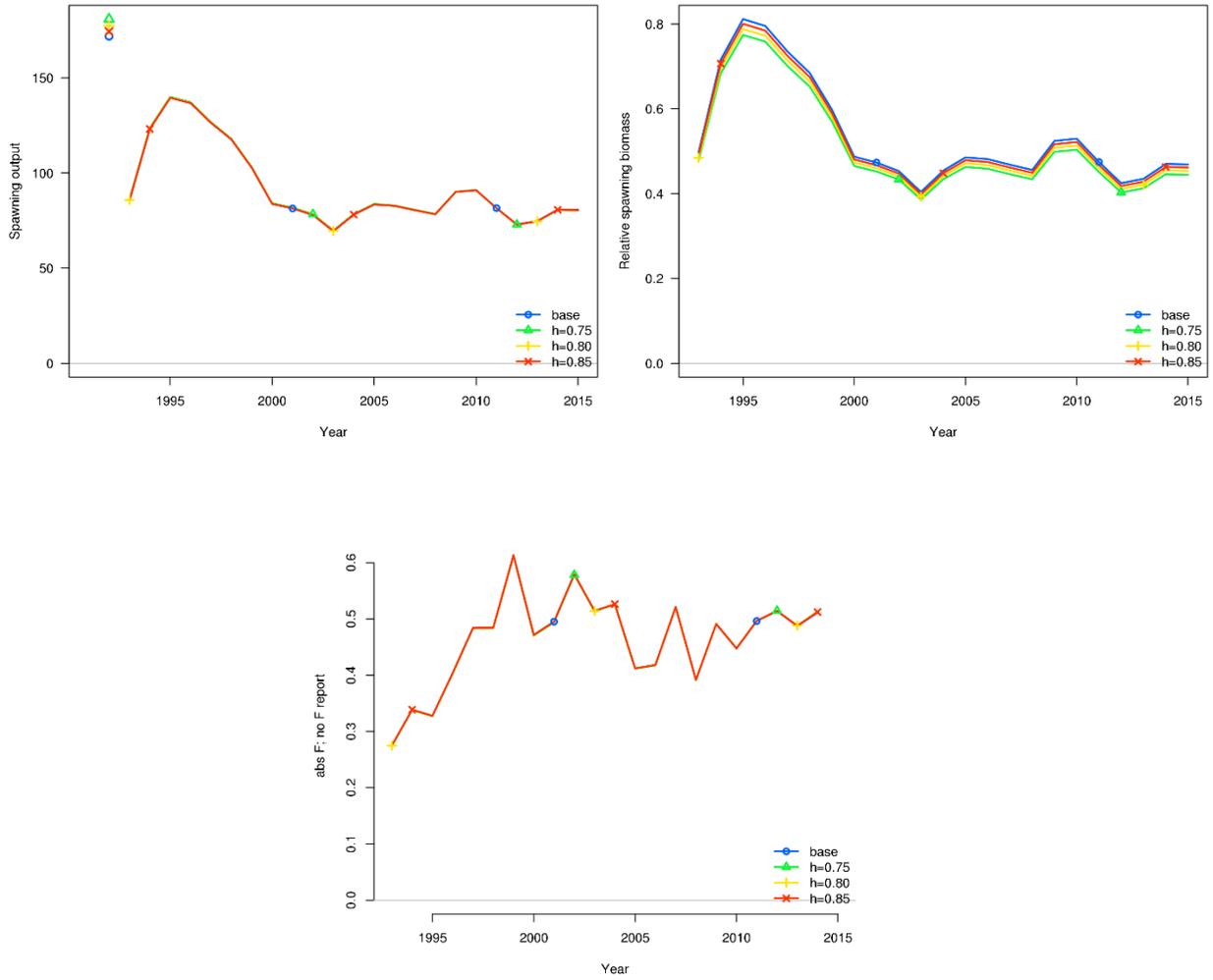
**Figure 5.17.** Estimated female spawning biomass (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the 2017 base case model (blue; h=0.90) and sensitivity runs using different stock-recruitment steepness (h=0.75; 0.80; 0.85) values. See Table 4.5 and Section 5.6.2 for details on sensitivity runs.
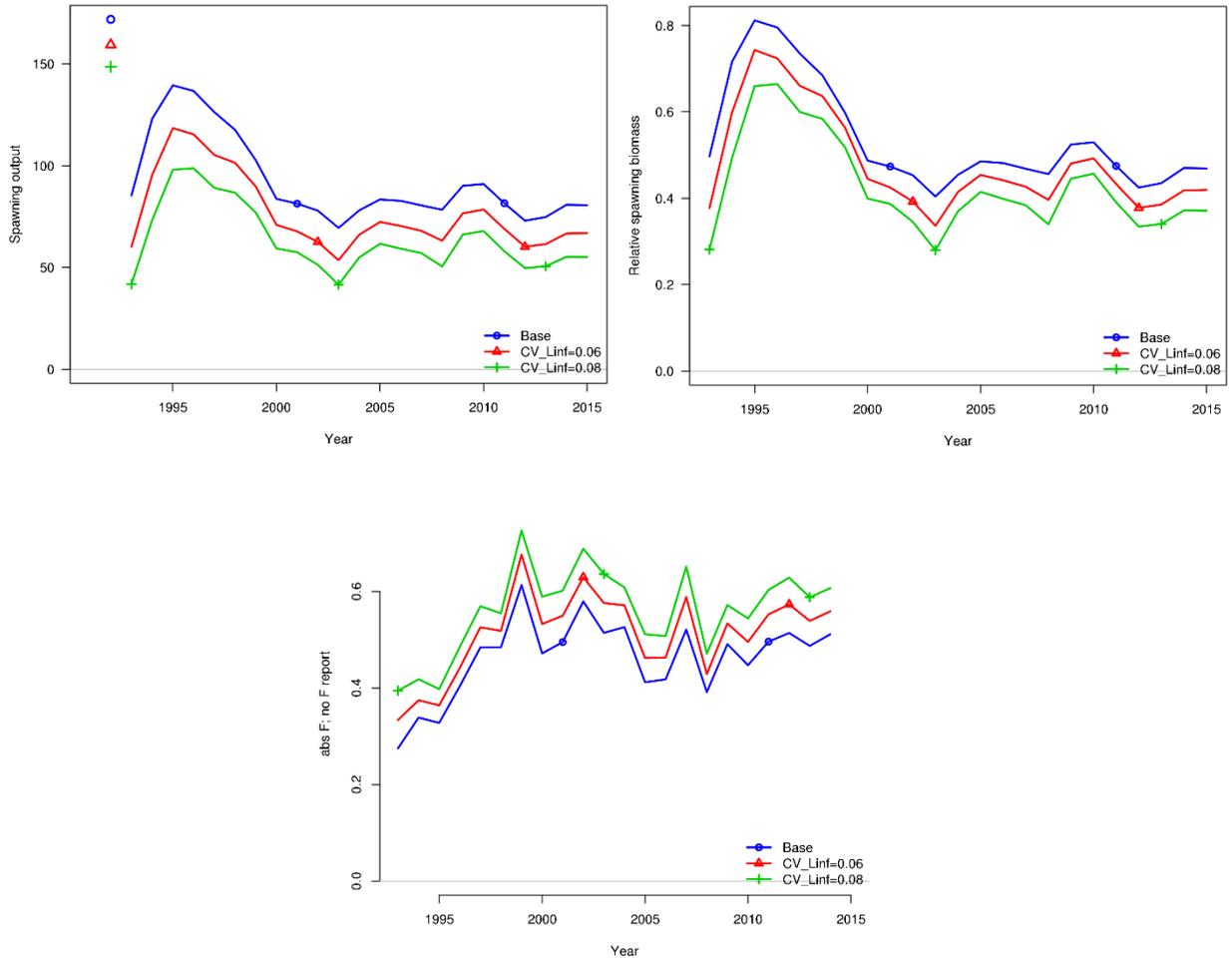
Figure 5.18. Estimated female spawning biomass (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the 2017 base case model (blue) and sensitivity runs using different CV values of the L_{inf} parameter. See Table 4.5 and Section 5.6.3 for details on sensitivity runs.
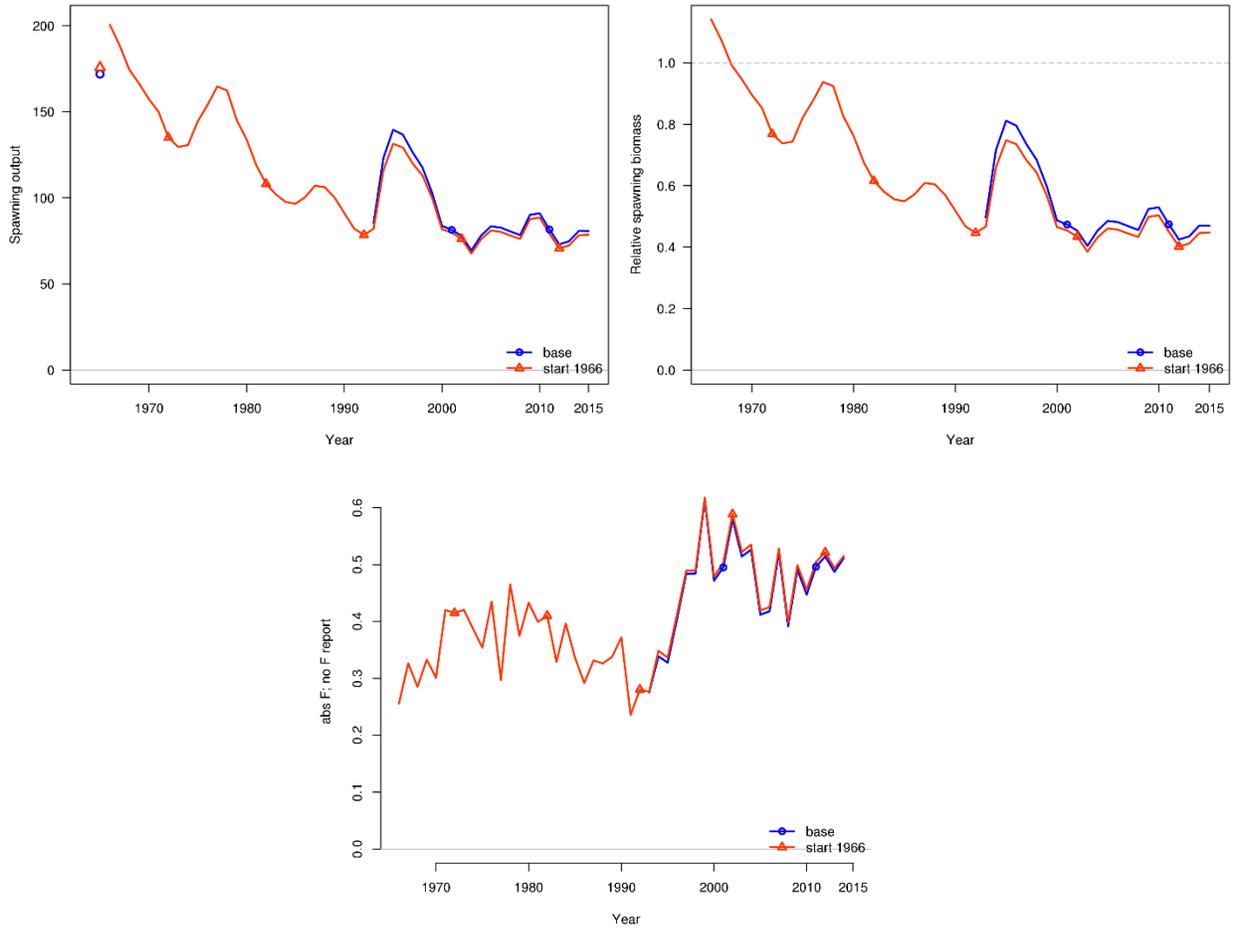
Figure 5.19. Estimated female spawning biomass (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the 2017 base case model (blue) and a sensitivity run using a start year of 1966. See Table 4.5 and Section 5.6.4 for details on sensitivity runs.
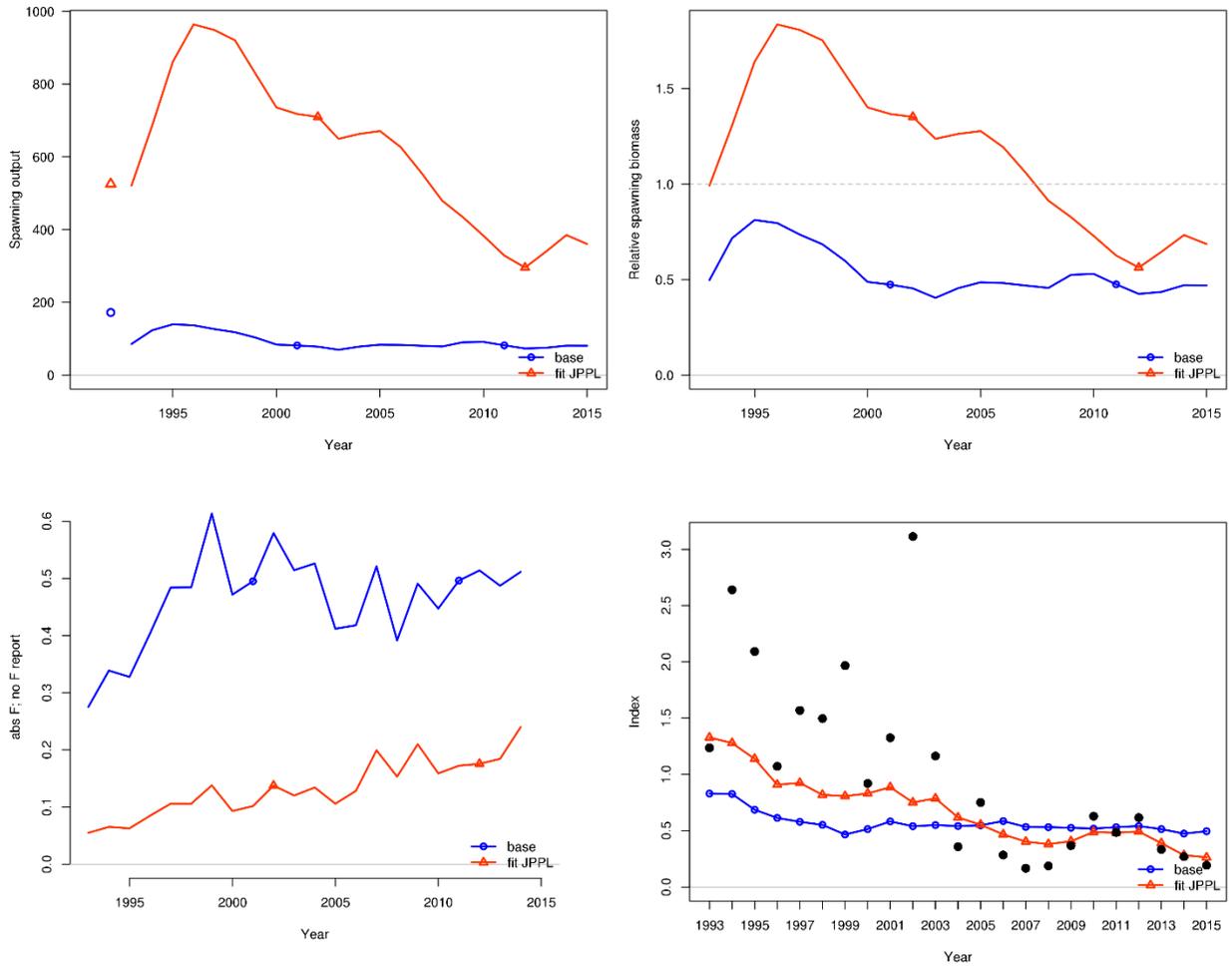
Figure 5.20. Estimated female spawning biomass (upper left), spawning depletion (upper right), fishing intensity (1-SPR) (lower left), and comparison between model predictions and observations of the Japanese pole-and-line (F17) index (lower right) for the 2017 base case model (blue), which did not fit to the F17 index, and a sensitivity run that fitted to the F17 index (red). Black circles and colored lines in the lower right panel indicate the F17 index observations and expectations respectively. See Table 4.5 and Section 5.6.5 for details on sensitivity runs.
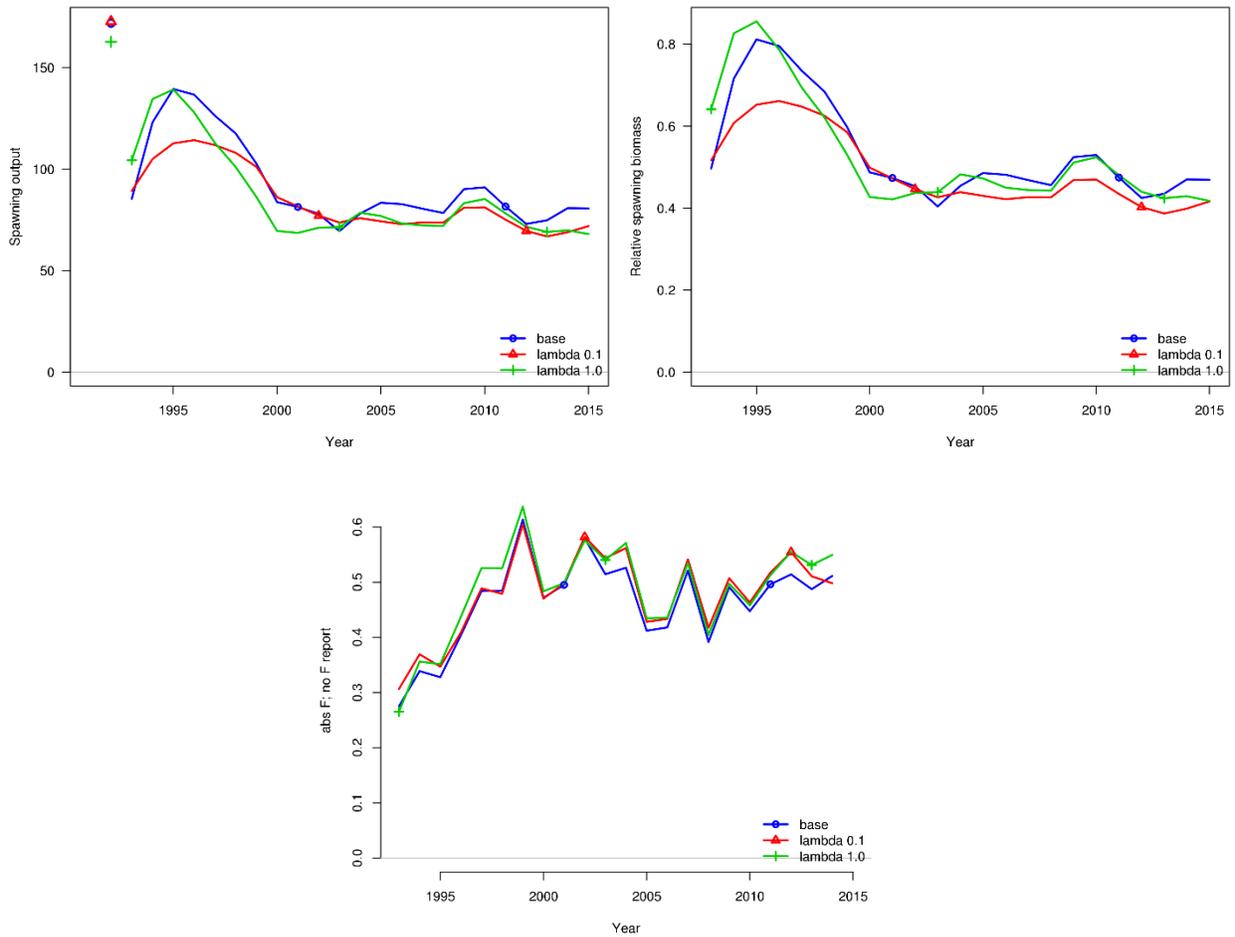
Figure 5.21. Estimated female spawning biomass (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the 2017 base case model (blue), where the size composition data of five fisheries were down-weighted (lambda=0.1), and sensitivity runs where the size composition data from all fisheries were fully weighted (lambda=1.0) or down-weighted (lambda=0.1). See Table 4.5 and Section 5.6.6 for details on sensitivity runs.
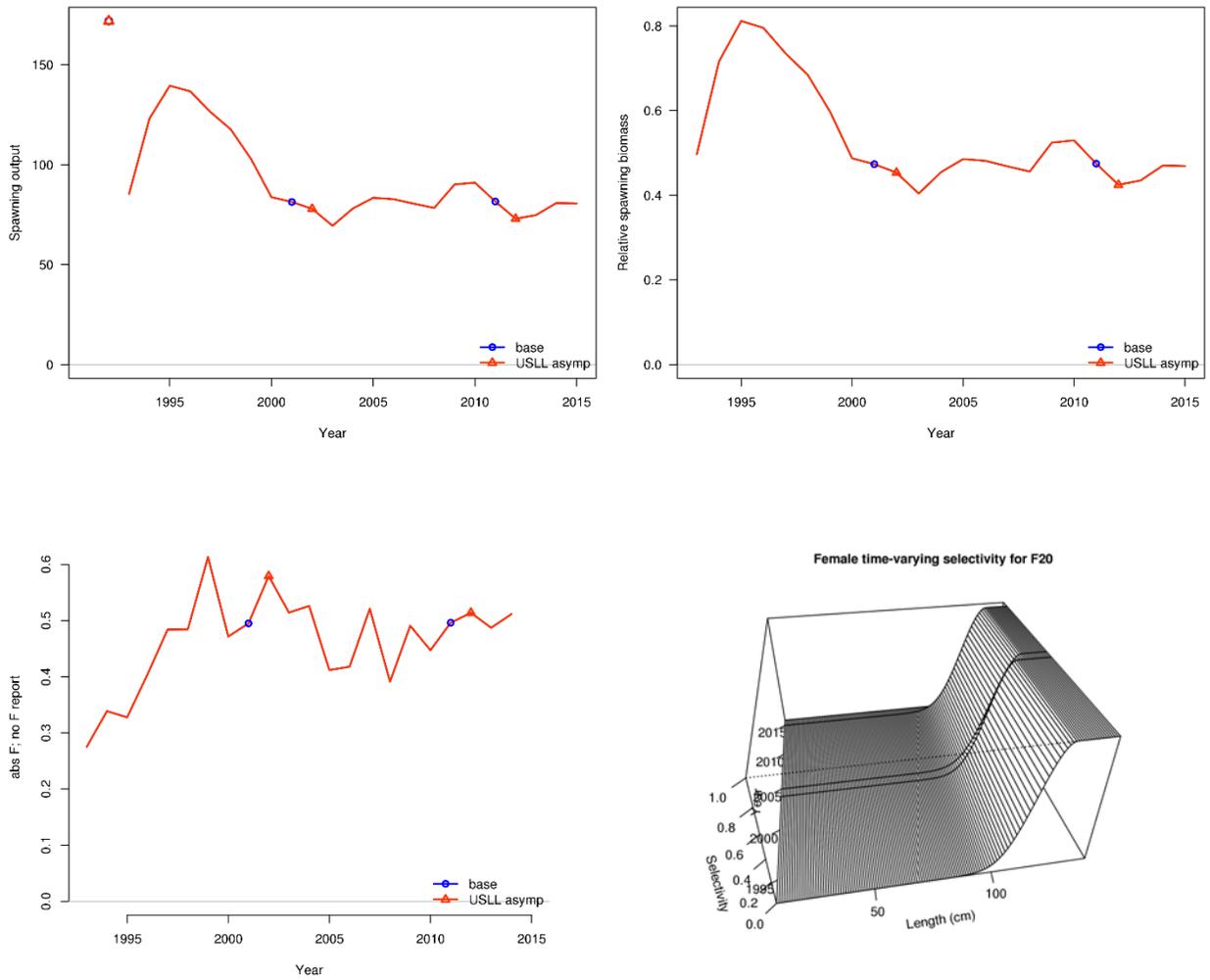
Figure 5.22. Estimated female spawning biomass (upper left), spawning depletion (upper right), fishing intensity (1-SPR) (lower left) for the 2017 base case model (blue), where the size selectivity of the F20 US longline fishery was allowed to be dome-shaped (see Fig. 5.9), and a sensitivity run where the F20 fishery was forced to have an asymptotic selectivity (lower right). See Table 4.5 and Section 5.6.7 for details on sensitivity runs.
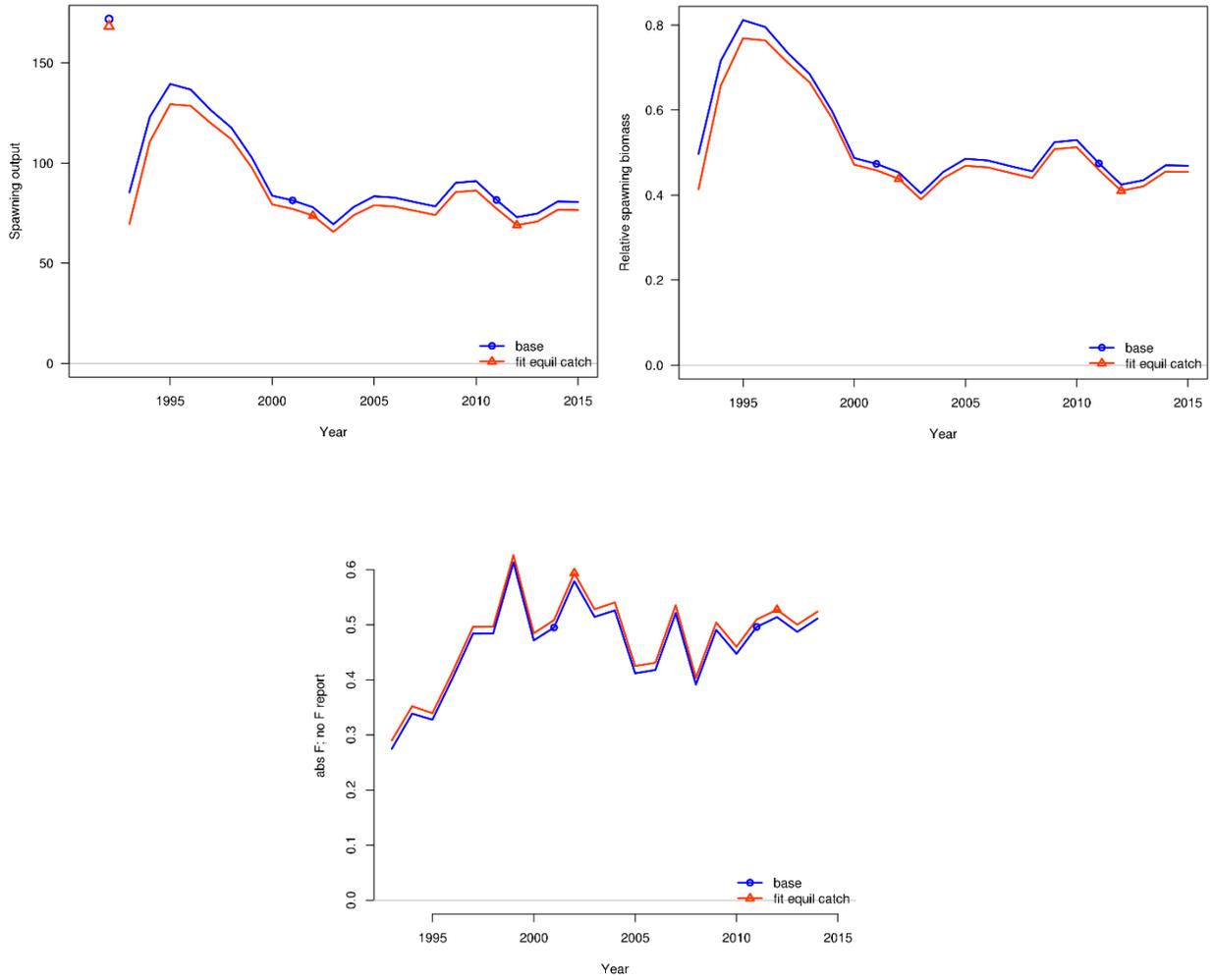
Figure 5.23. Estimated female spawning biomass (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the 2017 base case model (blue), and a sensitivity run that fit to the equilibrium catch of each fishery estimated as the average of 10 years of annual catch during 1983 - 1992. See Table 4.5 and Section 5.6.8 for details on sensitivity runs.
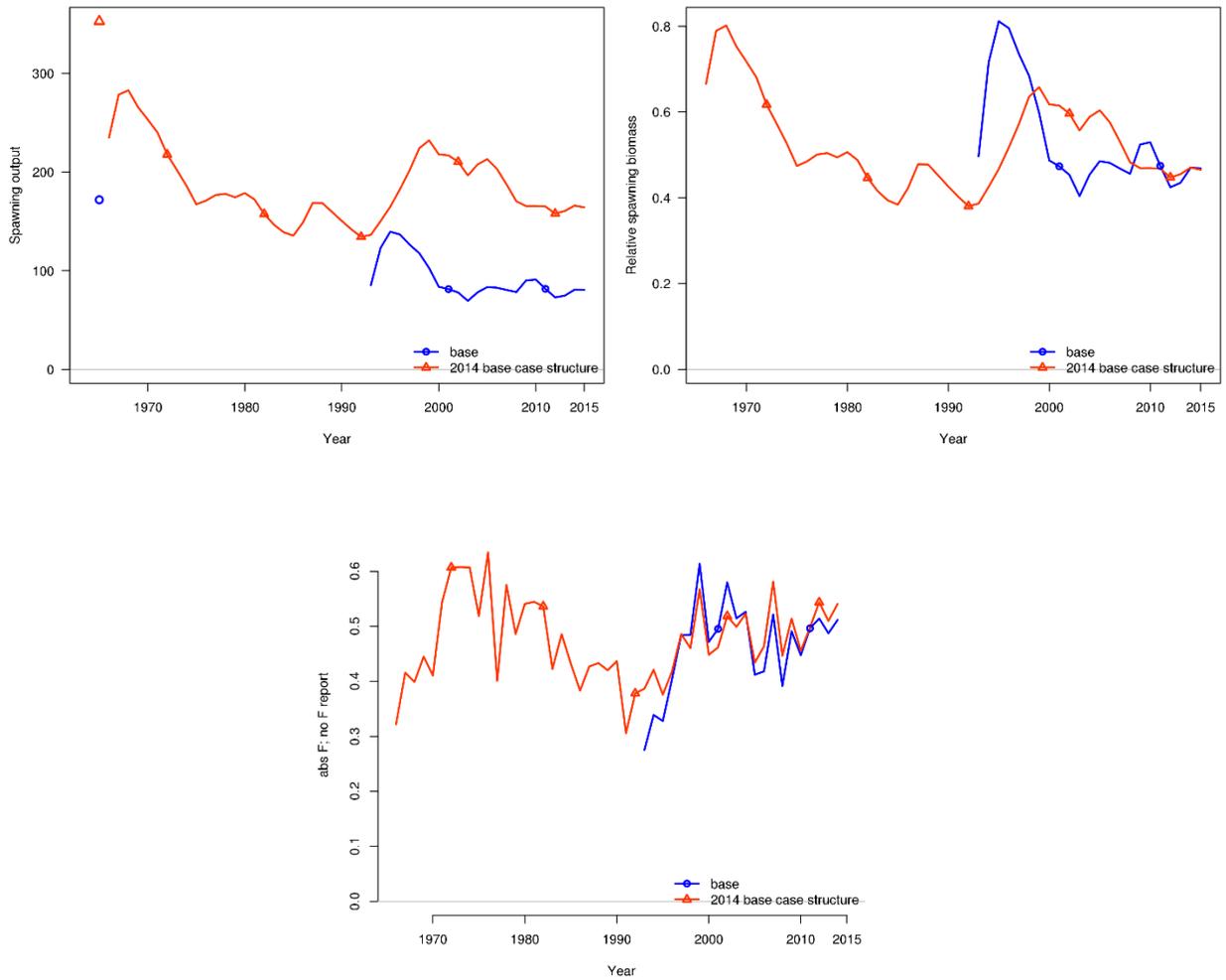
Figure 5.24. Estimated female spawning biomass (upper left), spawning depletion (upper right), and fishing intensity (1-SPR) (lower) for the 2017 base case model (blue), and a sensitivity run that followed closely the model structure of the 2014 base case model. See Table 4.5 and Section 5.6.9 for details on sensitivity runs.
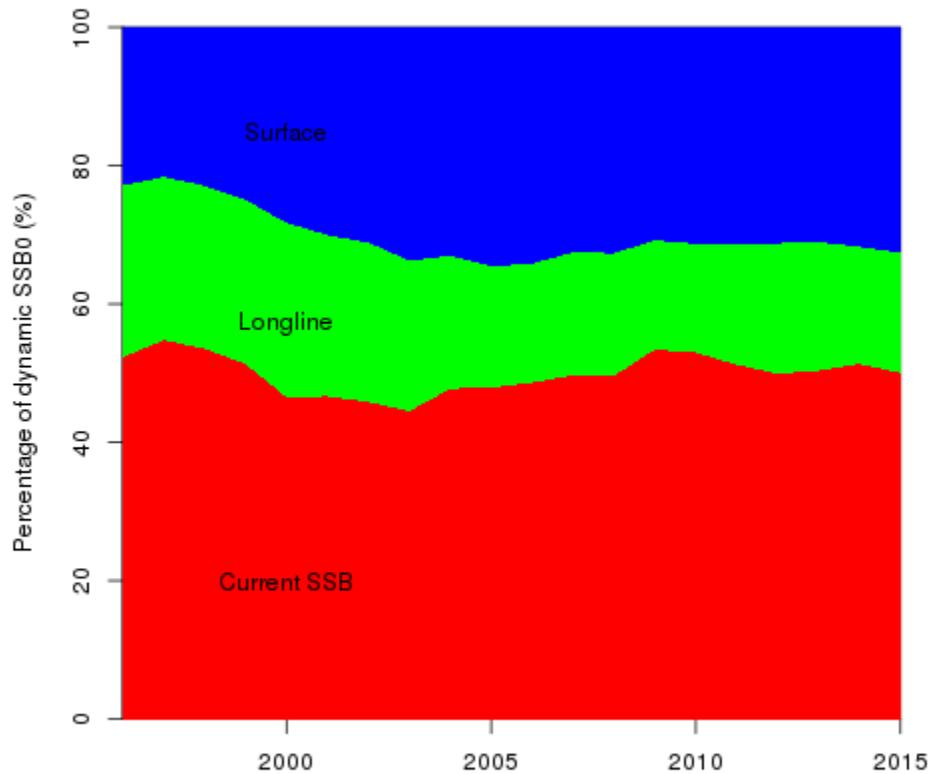
Figure 5.25. Fishery impact analysis on north Pacific albacore (*Thunnus alalunga*) showing female spawning biomass (SSB) (red) estimated by the 2017 base case model as a percentage of dynamic unfished female SSB (SSB_0). Colored areas show the relative proportion of fishing impact attributed to longline (USA, Japan, Chinese-Taipei, Korea and others) (green) and surface (USA, Canada, and Japan) (blue) fisheries (primarily troll and pole-and-line gear, but including all other gears except longline).
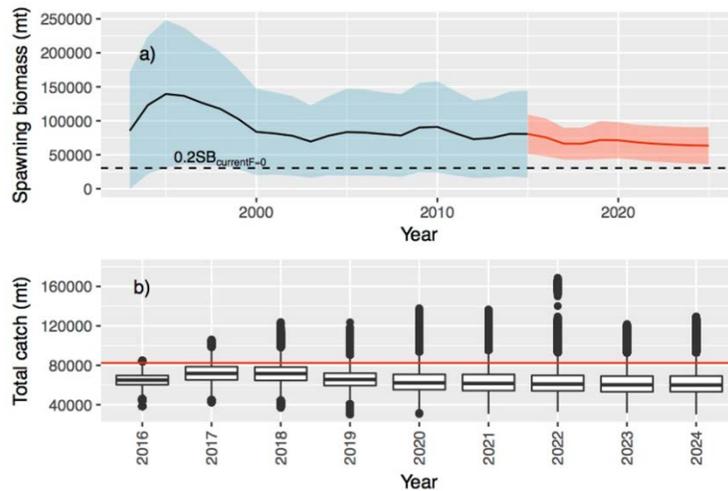
Figure 5.26. a) Historical and future trajectory of north Pacific albacore (*Thunnus alalunga*) female spawning biomass (SSB) under a constant fishing intensity ($F_{2012-2014}$) harvest scenario. Future recruitment was based on the expected recruitment variability and autocorrelation. Black line and blue area indicates maximum likelihood estimates and 95% confidence intervals (CI), respectively, of historical female SSB, which includes parameter uncertainty. Red line and red area indicates mean value and 95% CI of projected female SSB, which only includes future recruitment variability and SSB uncertainty in the terminal year. (b) Expected annual catch under a constant fishing intensity ($F_{2012-2014}$) harvest scenario (2016-2025). The red line is the current average catch (2010-2014 = 82,432 t).

Figure 5.27. (a) Historical and future trajectory of north Pacific albacore (*Thunnus alalunga*) female spawning biomass (SSB) under a constant catch (average 2010-2014 = 82,432 t) harvest scenario. Future recruitment was based on the expected recruitment variability and autocorrelation. Dashed line indictaes the average limit reference point threshold for 2012-2014. Black line and blue area indicates maximum likelihood estimates and 95% confidence intervals (CI), respectively, of historical female SSB, which includes parameter uncertainty. Red line and red area indicates mean value and 95% CI of projected female SSB, which only includes future recruitment variability and SSB uncertainty in the terminal year. (b) Projected fishing intensity relative to the current fishing inetnsity (2012-2014) (red line) under a constant catch scenario (average 2010-2014).