Supplementary Material

The full dynamics model described herein is a modified version of the 2018 stock assessment (ISC, 2018). The model is an age-structured and length-based forward simulation model in the Stock Synthesis software, version 3.24f (Methot and Wetzel, 2013). The stock assessment estimated dynamics from 1952 to 2016 using seasonal observations of catch and size compositions by the fleet as well as indices of relative abundance from fishery-dependent catch-per-unit-effort data (CPUE) (Fig. S1) to find the maximum likelihood estimates of all estimated parameters. CPUE indices of relative abundance are derived from Japanese longline and Taiwanese longline fisheries to inform trends in adult abundance. We call it the full dynamics model because the model fit to the size composition data and estimated annual recruitment events.

The catch was assumed well known and fit in the model assuming a lognormal error structure with a minimal observation error (coefficient of variation [CV]=0.1). Composition observation was fit assuming a multinomial error structure with observation error described by the sample size. For all fleets, the sample size was the estimate of the number of landing/haul/well measured or the number of sampled trips. Indices of abundance were fit assuming a lognormal error distribution with observation error taken from the standardization. A minimum average index CV at 0.2 for each series was assumed based on fitting a simple smoother to index observations outside the model and estimating the residual variance (ISC, 2018). The influence of each data observation was based on the input observation and process errors.

The key systems-modeled parameters (natural mortality, growth, and maturity) are seasonal were assumed to be the same for females and males and specified at predetermined values obtained (ISC, 2018). The maximum age bin was defined as an accumulator for all ages 20 and older. The natural mortality rate (*M*) was fixed at 1.6 for age 0, 0.386 year^{-1} for age 1 based on empirical estimates from tagging studies (Polacheck et al., 1997; Takeuchi and Takahashi, 2006), and 0.25 year^{-1} for age 2 and older. The von Bertalanffy growth parameters were fixed based on the age and growth studies (Shimose et al., 2009; Shimose and Ishihara 2015) using a growth coefficient of 0.188 year^{-1}, length at age 0 of 19.05 cm, length at age 3 of 118.57 cm, CV of length at age 0 of 0.259, and CV of length at age 3 and older of 0.044. CVs of length at age 1 and 2 were linearly interpolated between the CVs of length at age 0 and 3. Fish were assumed to be 20% mature at age 3, 50% mature at age 4, and 100% mature at age 5 and older.

Recruitment was assumed to occur in summer, while spawning activity primarily takes place in spring to summer. Recruitment was log-normally distributed about a mean recruitment. The unfished parameter of that relationship (ln R0) was estimated in the model and the steepness of the Beverton–Holt spawner-recruit relationship was fixed at 1.0 so that the magnitude of the deviations represents the same magnitude of actual recruitment irrespective of spawning biomass. The variability of the recruitment deviations was assumed to be 1.0 to be less constraining on the deviations. Non-equilibrium initial conditions were assumed by starting the model at a depleted level (i.e., through estimating equilibrium fishing mortality rates) and including recruitment deviations for 11 years prior to the model's starting year. Bias correction of the recruitment was 0 for these early years and 0.95 for the modeling years (Methot and Taylor, 2011).

The initial conditions of the model estimated equilibrium fishing mortality rates without fitting to an equilibrium catch, which resulted in the model starting at a level of depletion consistent with the data and model structure during the dynamic period. The catchability coefficient for each index (observation-modeled parameter) was derived assuming that observed biomass is proportional to available biomass. Selectivity pattern by fleet was a combination of both a length-based (gear component) and age-based (availability component) (Table S1). All fleets allowed for domed-shaped gear selection except for the Taiwanese fleet which assumed a logistic shape. Age-based selection by fleet estimated time-varying age-specific selectivity parameters for fleets that caught migrating ages and specified age selection=1 (fully selected) for fleets that caught non-migrating age groups (primarily longline fleets) (Lee et al., 2017). This results in estimating 237 selectivity parameters out of total 320 estimated parameters.

The model fits the size modes in data aggregated by fishery and season fairly well (Fig. S2). Predicted abundance indices with variation were generally within 95% CI for all of observed abundance indices (Fig. S3). In particular, the model fit well to the S2, S3 (Japanese longline early and middle periods); the root-mean-squared-error (RMSE) between observed and predicted abundance indices for these indices were close to or less than 0.2, which was the input CVs for these indices. The model also fit to the terminal indices of S1 and S4, which were Japanese and Taiwanese longline CPUEs (RMSE ≤ 0.3).

PBF have been heavily exploited across all age groups and the majority of the PBF catch, in terms of numbers, consists of age-0 fish (Fig. S4). The unfished spawning stock biomass (SSB0) was estimated to be about 846,700 t (R0 = 18 million fish). The SSB estimates also exhibited long term fluctuations (Fig. S5). Historical recruitment estimates have fluctuated since 1952 without an apparent trend.

References

ISC (International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean).

2018. Stock assessment of Pacific bluefin tuna (*Thunnus orientalis*) in the Pacific Ocean in 2018. Report of the Pacific Bluefin Tuna Working Group. Annex 14. 18 meeting of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean, Yeosu, Republic of Korea, July 11–16, 2018. Int. Sci. Comm. Tuna Tuna-like Species North Pac. Ocean ISC/18/ANNEX/14, 147 p. [Available at https://isc.fra.go.jp/reports/isc/isc18_reports.html.]

Lee, H. H., K. R. Piner, M. Maunder, I. G. Taylor, and R. D. Methot.

2017. Evaluation of alternative modelling approaches to account for spatial effects due to age-based movement. Can. J. Fish. Aquat. Sci. 74:1832–1844. https://doi.org/10.1139/cjfas-2016-0294

Methot, R. D., Jr, and C. R. Wetzel.

2013. Stock Synthesis: a biological and statistical framework for fish stock assessment and fishery management. Fish. Res. 142:86–99. https://doi.org/10.1016/j.fishres.2012.10.012

Methot, R. D., Jr, and I. Taylor.

2011. Adjusting for bias due to variability of estimated recruitments in fishery assessment models. Can. J. Fish. Aquat. Sci. 68:1744–1760. https://doi.org/10.1139/f2011-092

Polacheck, T., W. S. Hearn, C. Miller, W. Whitelaw, and C. Stanley.

1997. Updated estimates of mortality rates for juvenile SBT from multi-year tagging of cohorts. Comm. Conserv. South. Bluefin Tuna Doc. CCSBT-SC/97/26.

Shimose, T., T. Tanabe, K. S. Chen, and C. C. Hsu.

2009. Age determination and growth of Pacific bluefin tuna, *Thunnus orientalis*, off Japan and Taiwan. Fish. Res. 100:134–139. https://doi.org/10.1016/j.fishres.2009.06.016.

Shimose, T., and T. Ishihara.

2015. A manual for age determination of Pacific Bluefin tuna *Thunnus orientalis*. Bull. Fish. Res. Agen. 40:1–11.

Takeuchi, Y., and M. Takahashi.

2006. Estimate of natural mortality of age 0 Pacific bluefin tuna from conventional tagging data. Int. Sci. Comm. Tuna Tuna-like Species North Pac. Ocean, Work. Group Rep. ISC/06/PBFWG/07.

Table S1. Fishery-specific selectivity and their attributes used in the full model for Pacific bluefin tuna (*Thunnus orientalis*)

Fleet name	**Ages of fish caught**	**Length-based contact selectivity**	**Age-based availability**	**Time-varying**
F1JLL	Spawners	Dome-shaped (double normal)	None	None
F2JSPPS	Age 0	Dome-shaped (double normal)	None	None
F3KOLPS	Age 0	Mirror to F2		
F4TPSJS	Migratory ages (ages 1-5)	Asymptotic (logistic)	Age-specific (ages 3-9)	Ages 3-7 for 2000-2016
F5TPSPO	Migratory ages (ages 1-5)	Asymptotic (logistic)	Age-specific (ages 1-10)	Ages 1, 5-7 for 2004-2005
F6JTroll	Age 0	Dome-shaped (double normal)	None	None
F7JPL	Age 0	Mirror to F6		
F8JSN	Migratory ages (ages 1-5)	Asymptotic (logistic)	Age-specific (ages 1-4)	None
F9JSN	Migratory ages (ages 1-5)	Asymptotic (logistic)	Age-specific (ages 1-5)	None
F10JSN(HK_AM)	Migratory ages (ages 1-5)	Asymptotic (logistic)	Age-specific (ages 1-3)	None
F11JOthers	Migratory ages (ages 1-5)	Mirror to F10		
F12TWLLSouth	Spawners	Asymptotic (logistic)	None	None
F13USCOMM	Migratory ages (ages 1-5)	Dome-shaped (double normal)	None	Double normal for 1954-1981
F14MEXCOMM	Migratory ages (ages 1-5)	Dome-shaped (double normal)	None	Double normal for 2006-2016
F15EPOSports	Migratory ages (ages 1-5)	Mirror to F13		
F16JTroll4Pen	Age 0	None	100% selected at age 0	None
F17TWLLNorth	Spawners	Dome-shaped (double normal)	None	None
F18JSPPS	Migratory ages (ages 1-5)	Dome-shaped (double normal)	Age-specific (age 1)	Ages 1 for 2004-2012
F19JTroll	Age 0	Dome-shaped (double normal)	None	None

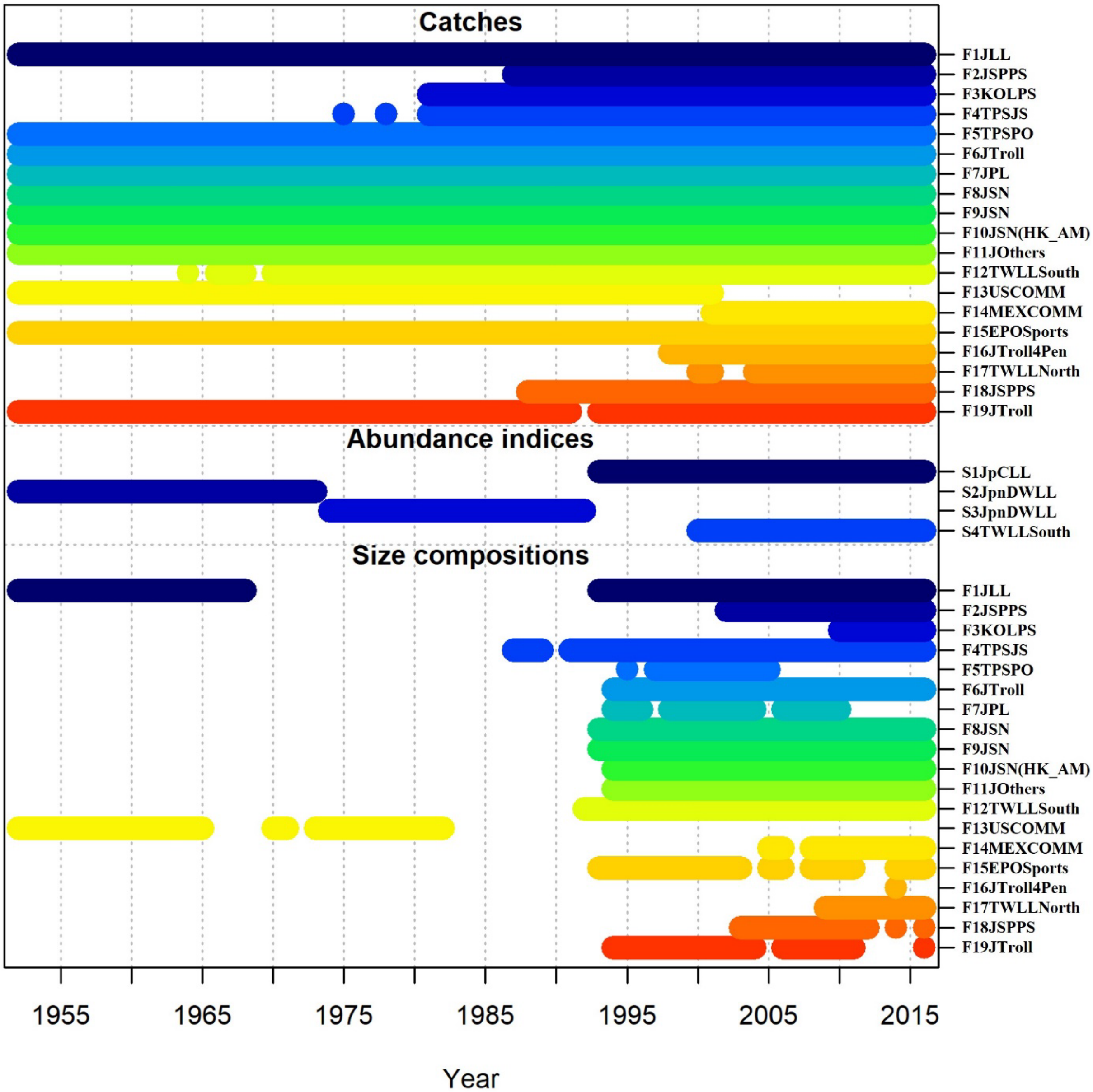

Figure S1. Data sources and fleet definition used in the study. Western Pacific longline (Fleets 1, 12, 17) with indices (Japanese fisheries S1-S3 and Taiwanese fisheries S4), Western Pacific purse seine for small fish (Fleets 2, 3, and 18), Western Pacific purse seine (Fleets 4 and 5), Western Pacific coastal fisheries (Fleets 6-11, 16, and 19), and Eastern Pacific fisheries (Fleets 13-15).

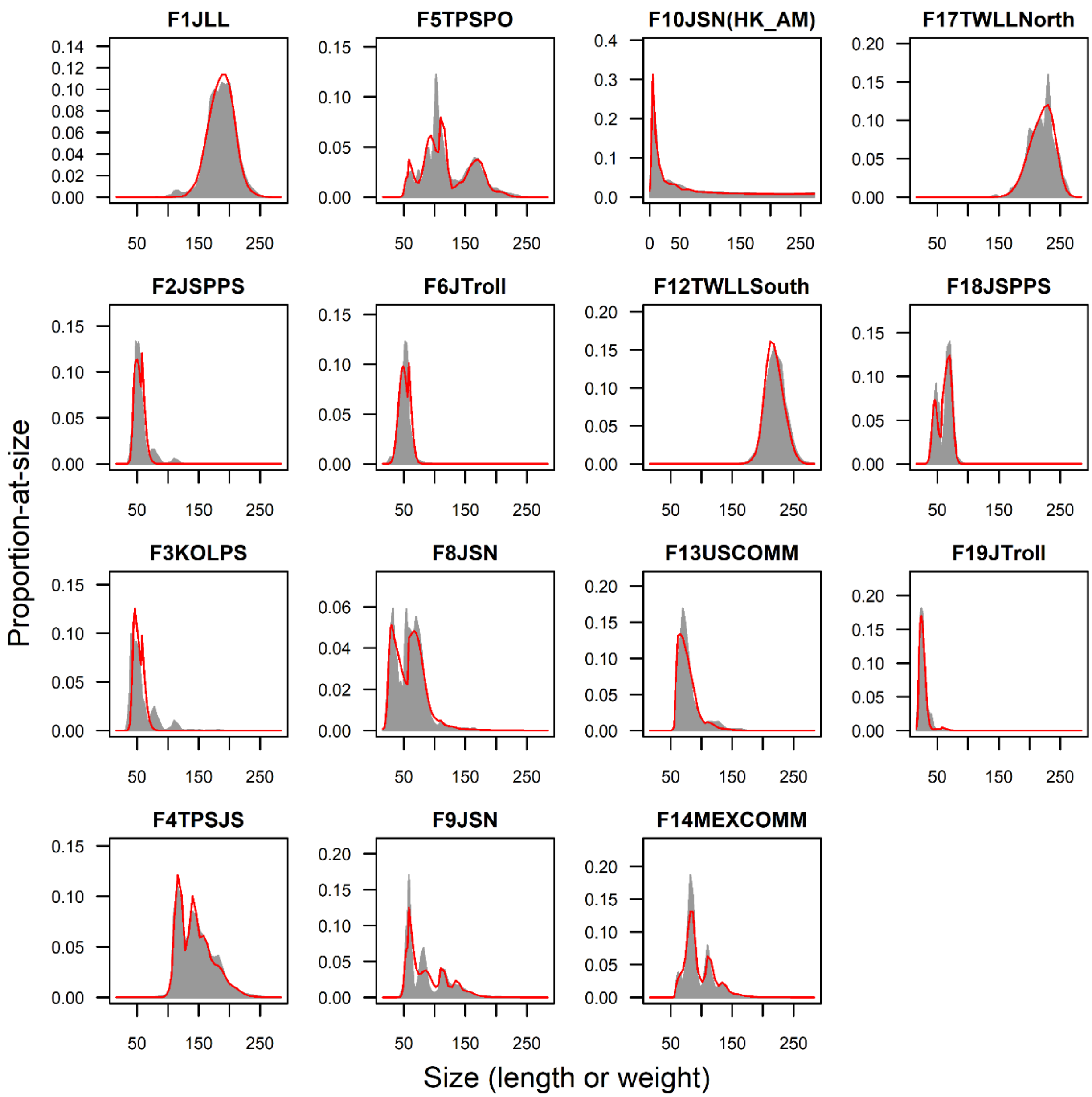

Figure S2. Overall fits (red lines) to the size compositions by fleet across seasons, where gray areas indicate the observations.

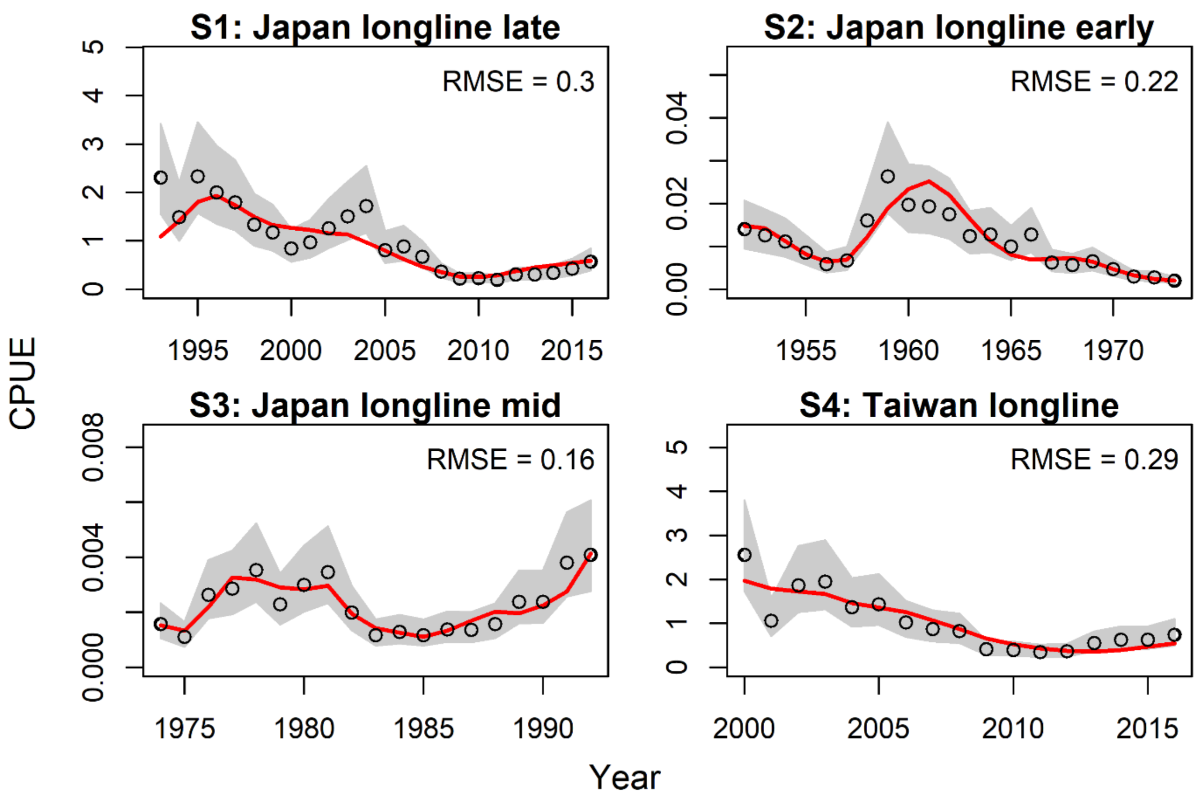

Figure S3. Predicted (red lines) and observed (open dots) abundance indices by fishery, where gray areas represent the 95% CI of observations. Root mean square error (RMSE) shows at the upper left corner.

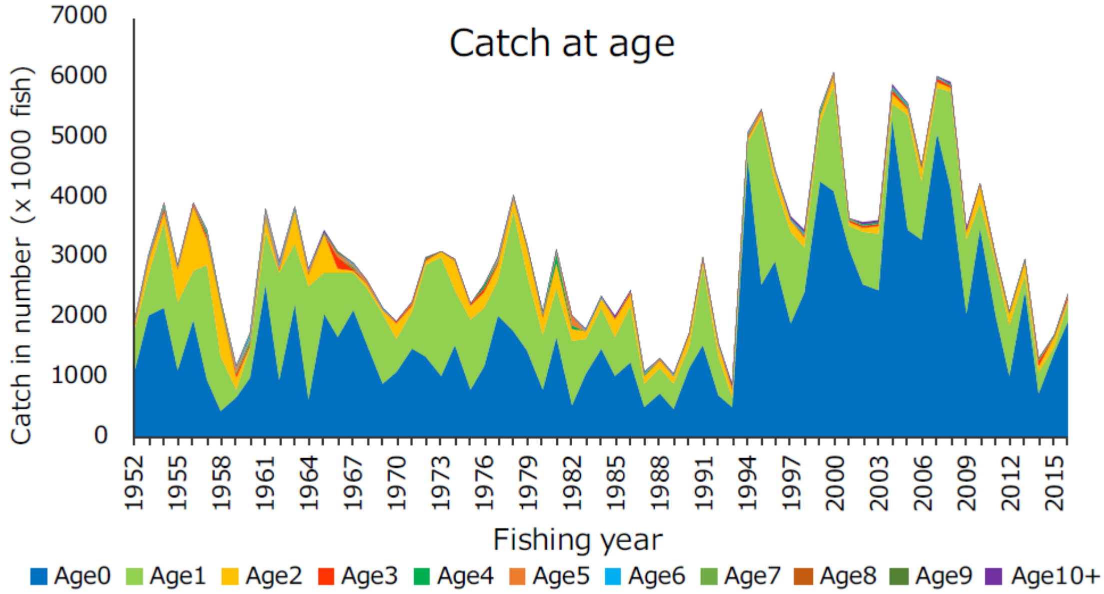

Figure S4. Annual catch (numbers) of Pacific bluefin tuna by age.

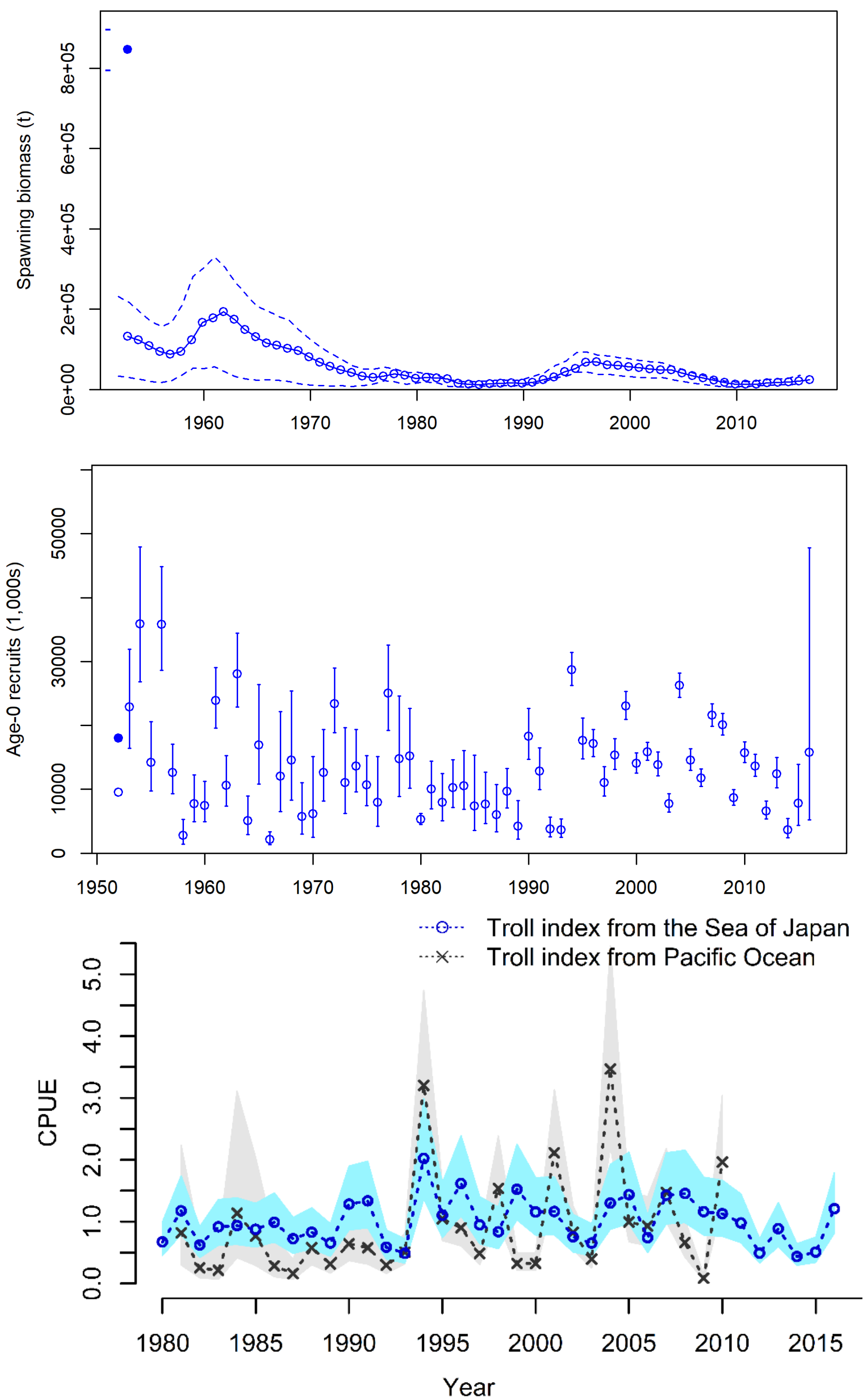

Figure S5. Spawning stock biomass (top), recruitment (middle), and age-0 troll indices (bottom), where the with open dots indicates point estimates, and the dashed lines (top), vertical lines (middle), and the areas (bottom) indicate the 95% confidence intervals. The solid dots show the unfished estimates. The uncertainty of the terminal (2016) recruitment estimate is higher than in previous years as these cohorts would not yet have made it to the longline fleets.