Supplementary Material

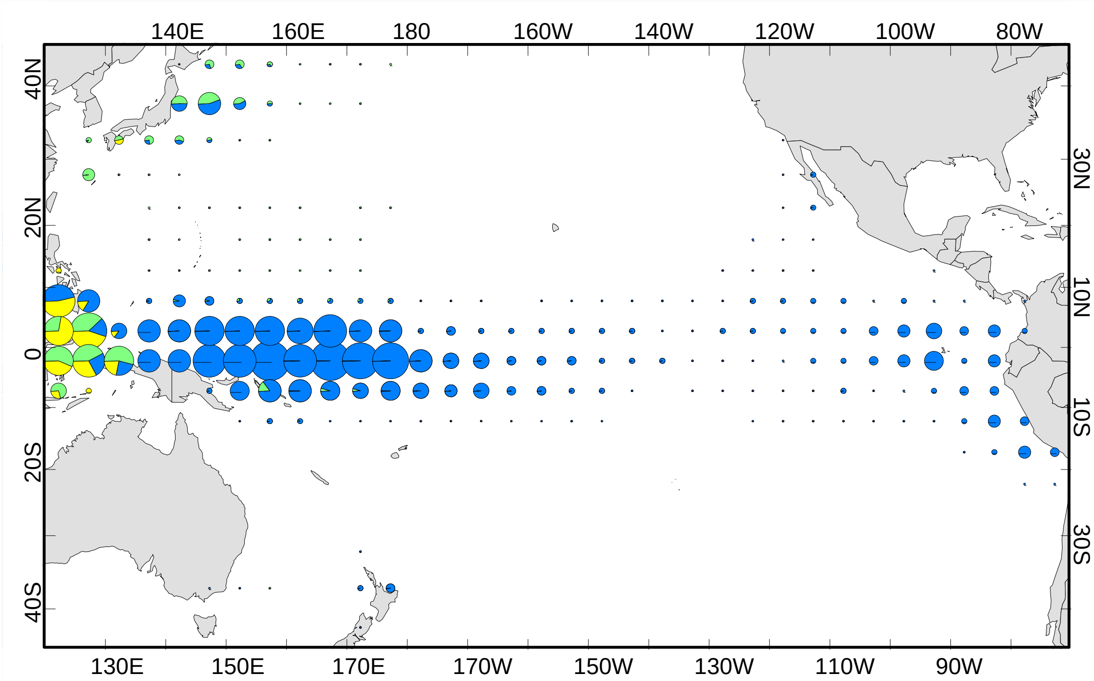
1 Spatial management zones in the Pacific Ocean of relevance to tuna fisheries

Supplementary Table 1. Existing spatial management zones in the Pacific Ocean of relevance to tuna fisheries. Prior tuna catch levels are the approximate average annual tuna catches in the five years prior to implementation.

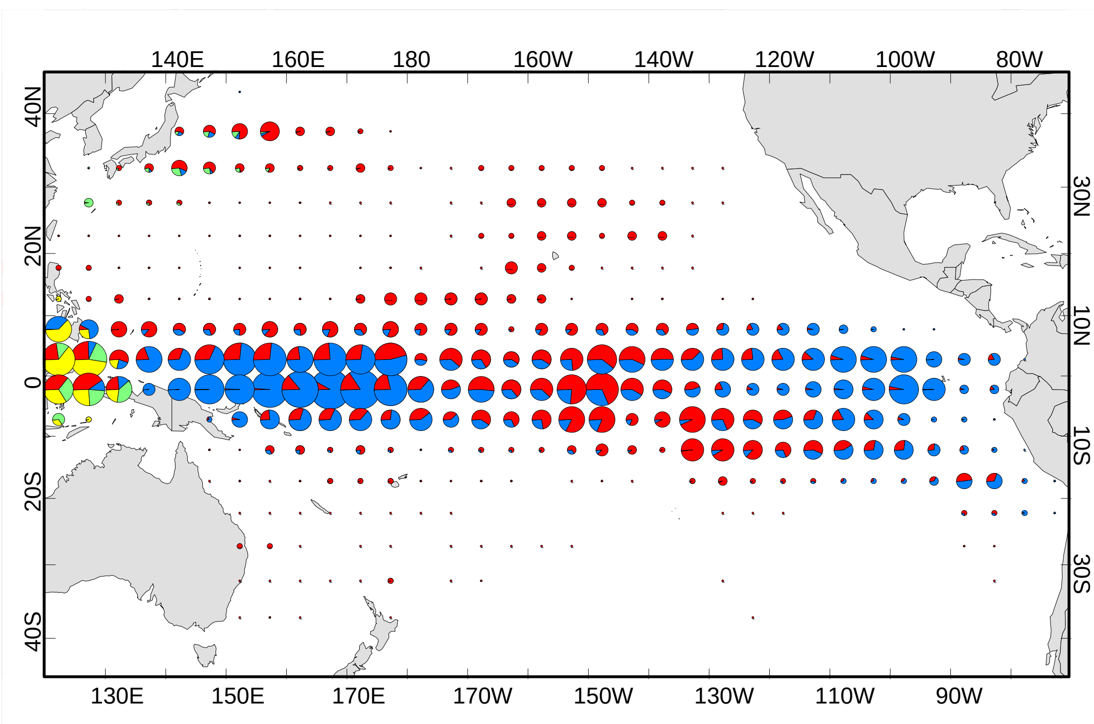
Name	Area	Size (km^2)	Date declared	Designation	Prior tuna catch level (t)
Marae Moana	Cook Islands	1,900,000	13 Jul 2013	Multiple-use MPA	~12,000
Papahānaumokuākea National Marine Monument	NW Hawaiian Islands	1,508,870	15 Jun 2006	Commercial no-take	~3,000
Pacific Remote Islands Marine National Monument	Baker, Howland and Jarvis Islands, Johnston, Wake and Palmyra Atolls, Kingman Reef	1,282,534	1 Jan 2009, extended 2014	Commercial no-take	~4,000
Natural Park of the Coral Sea	New Caledonia	1,270,000	23 Apr 2014	Multiple-use MPA, with no-take zones	~2,000
Coral Sea Marine Park	NE Australia	989,836	1 Jul 2018	Multiple-use MPA, with commercial no-take zones (238,400 km^2)	<1,000
Pitcairn Islands Marine Reserve	Pitcairn Islands	840,000	18 Mar 2015	Commercial no-take	<100
Palau National Marine Sanctuary	Palau	475,077	1 Jan 2020	Commercial no-take	~9,000
Phoenix Islands Protected Area	Phoenix Islands, Kiribati	405,755	1 Jan 2015	Commercial no-take	~100,000

2 Spatial distribution of catches

Skipjack tuna



Bigeye tuna



Supplementary Figure 1. Distribution of skipjack and bigeye tuna catches by longline (red), purse seine (blue), pole-and-line (green) and other gears (yellow) during 1998-2019. Catches (in weight) are proportional to the area of the circles (scaled differently for the two species).

3 Downscaling SEAPODYM skipjack and bigeye tuna models from 2° to 0.25° spatial resolution

3.1 Ocean forcing

For the MPA simulation the reference numerical models for skipjack and bigeye (Senina et al., 2020, 2021) originally parametrised and validated at coarse 2° spatial resolution were downscaled to allow representation of population dynamics at smaller spatial scales. An eddy-permitting resolution allows a representation of mesoscale activity that may be critical to consider, e.g., for larval retention processes occurring in MPAs.

We used new physical forcing variables (temperature and currents) provided by the eddy-permitting global ocean hindcast simulated by the global general circulation model NEMO with the ORCA025 configuration (Madec et al., 2008). This simulation was produced in the framework of the GLORYS project (https://www.mercator-ocean.fr/en/ocean-science/glorys/). It is forced by the atmospheric reanalysis ERA-INTERIM, and the validity of its outputs relies on the quality of atmospheric reanalysis, since no observations are assimilated within physical model. The biogeochemical forcing variables (primary production, euphotic depth and dissolved oxygen) were derived from observations. Two fields of vertically-integrated primary production were computed from satellite Chlorophyll-a data using either the VGPM or Eppley-VGPM model (Behrenfeld and Falkowski, 1997; http://sites.science.oregonstate.edu/ocean.productivity). Note that the VGPM model provided better model performance in describing skipjack tuna data, while Eppley-VGPM was used in the development of the bigeye reference model. Euphotic depth was computed using an empirical model (Morel and Berthon, 1989). The dissolved oxygen fields were obtained from the World Ocean Atlas 1° monthly climatology (Garcia et al., 2010), and interpolated to the regular 0.25° grid. All forcing variables were processed for the period 1998–2019, with the lower limit being defined by the beginning of Chlorophyll-a observations.

3.2 Skipjack tuna

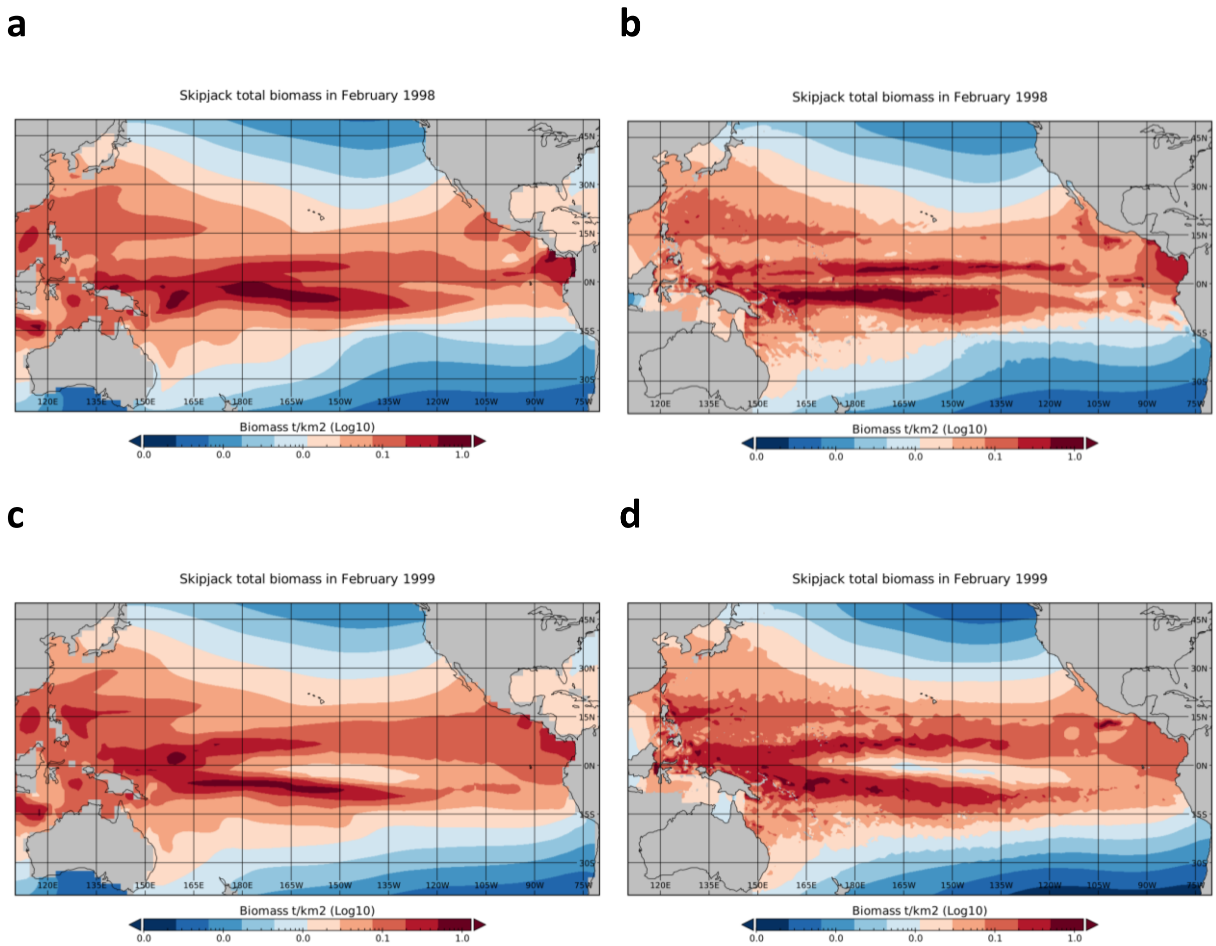
Because SEAPODYM spatial dynamics parameters, such as habitat and movement parameters, describe the link between population dynamics and the species environment, these parameters strongly depend on the ocean forcing. Hence, the validated MLE model (hereafter called 'reference' model) for skipjack tuna, which was developed under a different forcing simulated by the NEMO ORCA2 ocean model configuration with ERA-INTERIM atmospheric forcing and the PISCES biogeochemical model (Senina et al., 2020), cannot be used to simulate skipjack tuna dynamics with the new forcing variables. Therefore, the MLE solution of reference model was recalibrated under the new physical and biogeochemical forcing variables using the pseudo-observation method. This method consists of using predictions of the reference model as observations and estimating dynamic parameters using MLE method. The assumption that the spatial and age structure of the population predicted by the reference model are realistic is based on the reference model parameters being informed by large geo-referenced fishery and tagging data sets and the model predictions were validated with an independent dataset (Senina et al., 2020).

To recalibrate model parameters, the reference numerical model was downscaled from the original 2° to 1° spatial resolution. The 1° spatial resolution is a compromise between the fine resolution of the new forcing and reasonable computational times for the function minimization. The new model was configured at the 1° monthly resolution, and the new forcing variables were degraded to the 1° regular grid. A series of optimizations were done to recalibrate 1) spawning habitat parameters, 2) feeding habitat at two ages, age at first maturity and the 3-year-old age class, that is the last monthly class before the cumulative A+ class, and 3) the movement parameters. The spatio-temporal distribution of the reference model variables (spawning habitat index, feeding habitat indices and population densities) were extracted for the period 2006-2010 to be used as observational datasets. In theory, the movement rates do not need to be re-calibrated if the spatial structures of feeding habitat indices are the same as in the reference model. In practice, the perfect fit between feeding habitats is difficult to achieve due to different ocean dynamics and spatial distributions of prey species through pelagic layers achieved with the new forcing. Hence, at the final phase of parameter recalibration, the population densities of the unexploited population were fitted while estimating the movement rates as well as spawning and feeding habitat parameters. The model's initial conditions (spatial distributions of population densities at age) were provided by the reference model. The new MLE solution achieved in this pseudo-observation method was then used to run the model in the standard population dynamics simulation mode with fishing pressure and validated using fisheries data.

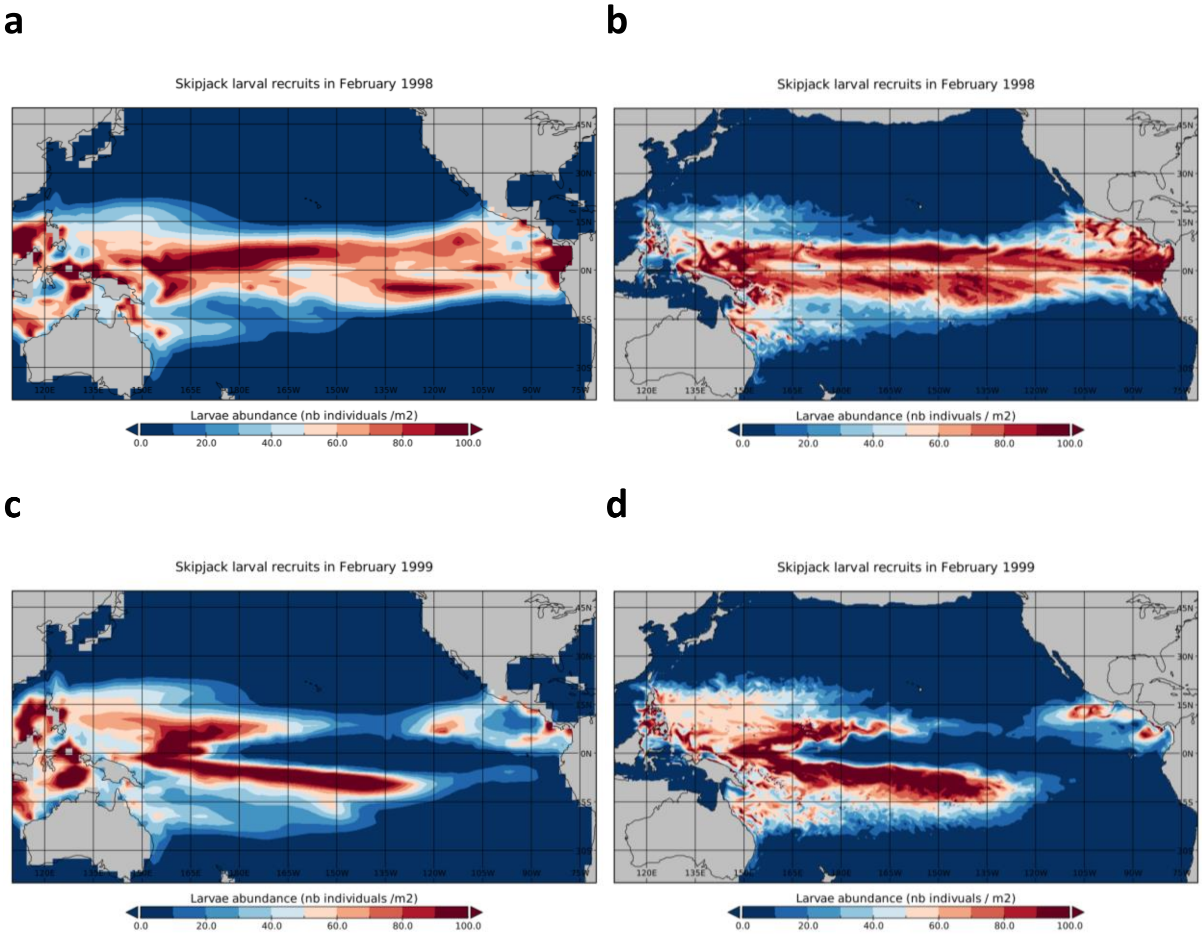
The downscaling of the 1° model to the 0.25° spatial resolutions consists simply of rescaling the model parameters that depend on spatial resolution. The control simulation was done with the initial conditions calculated by the coarse reference model for December 1997 and interpolated to the 0.25° regular grid. While the 0.25° resolution produces more patchy distributions of fish density compared to the coarse reference simulation (see Figure S3 and S4 for skipjack tuna), the downscaling method provides a close match of total abundance and spatial distribution between the two model configurations (Figure S5).

3.3 Bigeye tuna

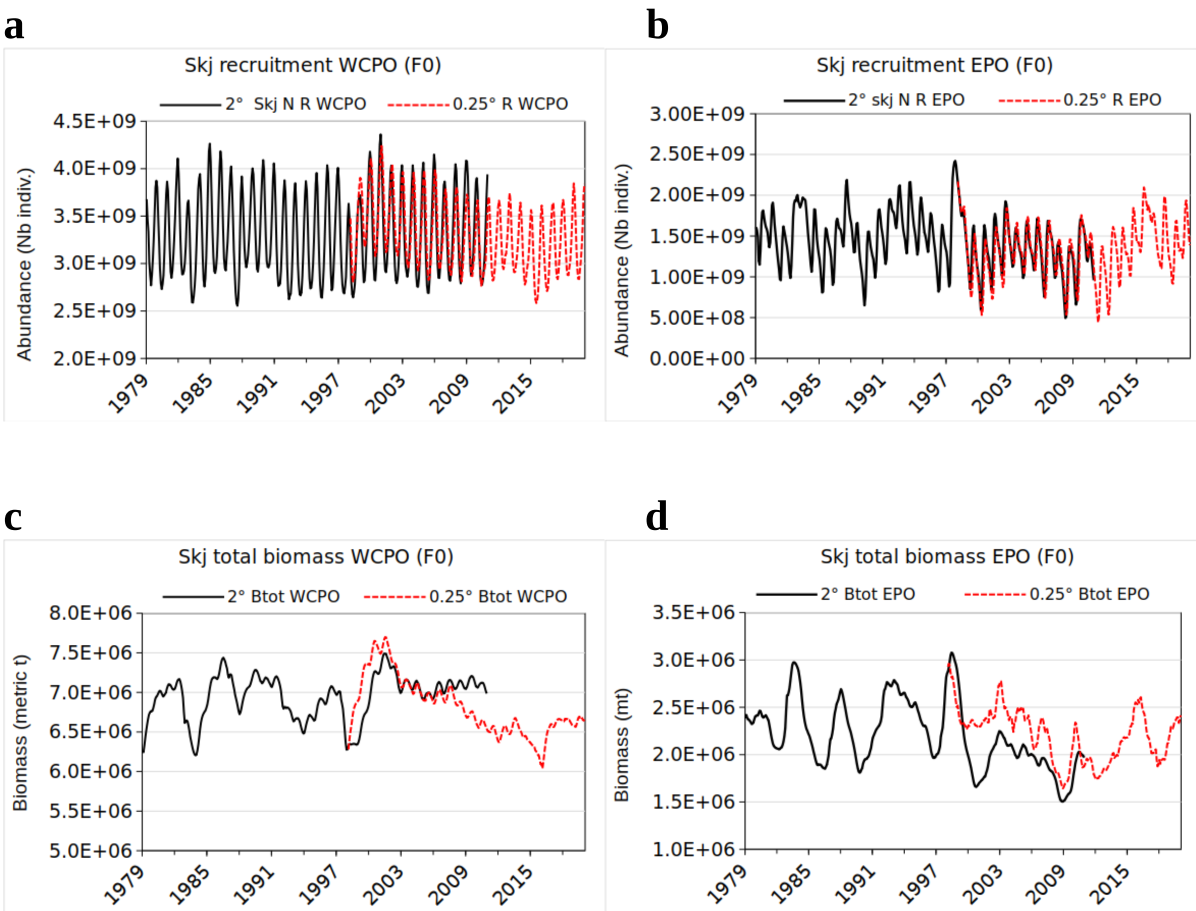
The bigeye reference model was originally developed with the new ocean forcing, which was however degraded to a coarse 2° resolution for computational purposes (Senina et al., 2021). Hence, only the rescaling of scale-dependent model parameters was necessary to obtain the fine-resolution bigeye reference model configuration used in this study.



Supplementary Figure 2. Skipjack tuna total biomass distributions estimated with interim 2° (a, c) and Glorys 0.25° (b, d) in February 1998 (*El Niño*; a, b) and February 1999 (*La Niña*; c, d).



Supplementary Figure 3. Skipjack tuna larval density distributions with interim 2° (a, c) and Glorys 0.25° (b, d) in February 1998 (*El Niño*; a, b) and February 1999 (*La Niña*; c, d).



Supplementary Figure 4. Time series of skipjack tuna recruitment (a, b) and total population biomass (c, d) estimated in the absence of fishing for the western and central Pacific Ocean (WCPO, west of 150°W; a, c) and eastern Pacific Ocean (EPO, east of 150°E; b, d) for the reference coarse simulation (1979-2010) and downscaled simulation (1998-2019) at 0.25° resolution.

4 Definition of fisheries used in the SEAPODYM models

Supplementary Table 2. Definition of skipjack tuna fisheries.

Code	Region	Nation	Gear/method	Resolution
P1	North of 20°N; 120°E-160°W	Japan	Pole-and-line	1°, month
P2	20°N–20°S; 140°E-150°W	Japan	Pole-and-line	1°, month
P3	20°N–20°S; 140°E-150°W	All except Japan	Pole-and-line	1°, month
S4	North of 20°N; 120°E-150°W	Japan	Purse seine	1°, month
S5	20°N–20°S; 140°E-150°W	All except Philippines, Indonesia, Vietnam	Purse seine associated sets (FAD, logs, animals)	1°, month
S6	8°S-20°N; 110°E-140°W	All except Philippines, Indonesia, Vietnam	Purse seine associated sets (FAD, logs, animals)	1°, month
S7	20°N–20°S; 140°E-150°W	All except Philippines, Indonesia, Vietnam	Purse seine free-school sets	1°, month
L8	North of 20°S	All	Longline	5°, month
O9	West of 140°E	Philippines, Indonesia, Vietnam	Small-scale miscellaneous fishing gears	1°, month
S10	East of 150°W	All	Purse seine associated sets (FADs and natural logs)	1°, month
S12	East of 150°W	All	Purse seine associated sets (whales and whale sharks)	1°, month
S13	East of 150°W	All	Purse seine free-school sets	1°, month
P15	East of 150°W	All	Pole-and-line	1°, month

Supplementary Table 3. Definition of bigeye tuna fisheries.

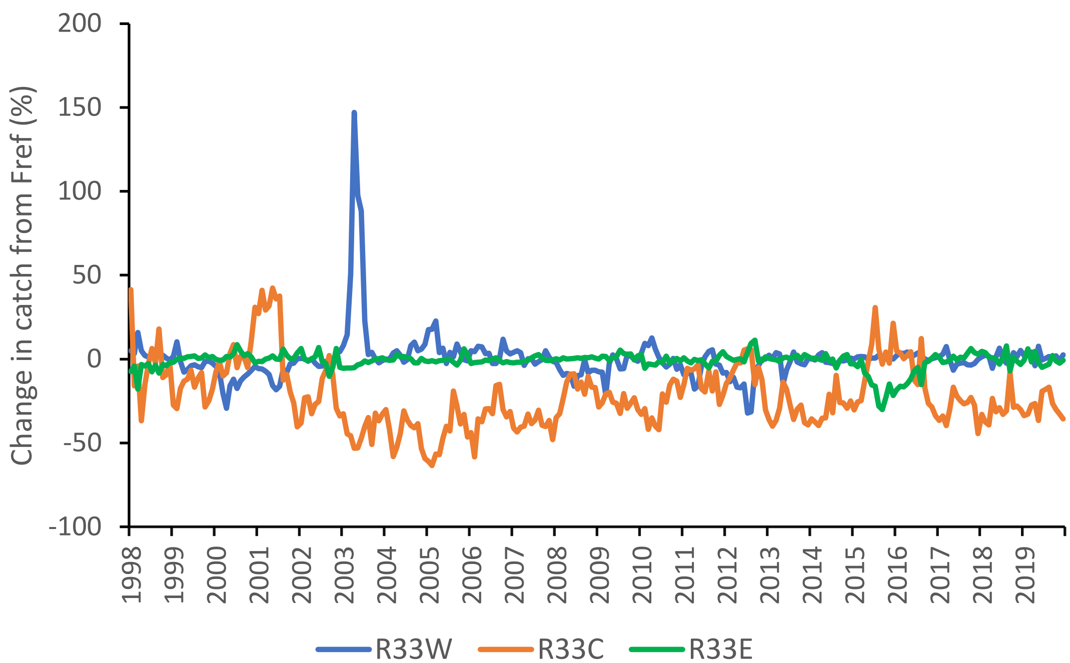
Code	Region	Nation	Gear/method	Resolution
L1	Pacific	Japan, Korea	Longline, bigeye target	5°, month
L2	Pacific	China, Taiwan	Longline, bigeye target	5°, month
L3	Pacific	Japan, Korea	Longline, yellowfin target	5°, month
L4	Pacific	China, Taiwan	Longline, yellowfin target	5°, month
L5	Pacific	Japan, Korea, China, Taiwan	Longline, albacore target	5°, month
L6	West of 140°E	Philippines, Indonesia, Vietnam	Longline	5°, month
L7	Pacific	Australia, New Zealand, USA	Longline, bigeye target	5°, month
L8	Pacific	Australia, New Zealand, USA	Longline, mixed target	5°, month
L9	Pacific	Pacific Islands countries and territories	Longline, bigeye target	5°, month
L10	Pacific	Pacific Islands countries and territories	Longline, mixed target	5°, month
L11	Pacific	Pacific Islands countries and territories	Longline, albacore target	5°, month
S12	West of 150°W	Korea, Taiwan, Papua New Guinea	Purse seine free-school sets	1°, month
S13	Pacific	Others	Purse seine free-school sets	1°, month
S14	West of 150°W	All	Purse seine natural log sets	1°, month
S15	West of 150°W	Korea, Taiwan, Papua New Guinea	Purse seine FAD sets	1°, month
S16	Pacific	Others	Purse seine FAD sets	1°, month
S17	East of 150°W	Ecuador, El Salvador	Purse seine FAD sets	1°, month
S18	East of 150°W	All	Purse seine marine mammal sets	1°, month
P19	Pacific	All	Pole-and-line	5°, month
O20	West of 140°E	Philippines, Indonesia, Vietnam	Small-scale miscellaneous fishing gears	5°, month

5 Estimated contribution of PIPA to wider stocks of skipjack and bigeye tuna

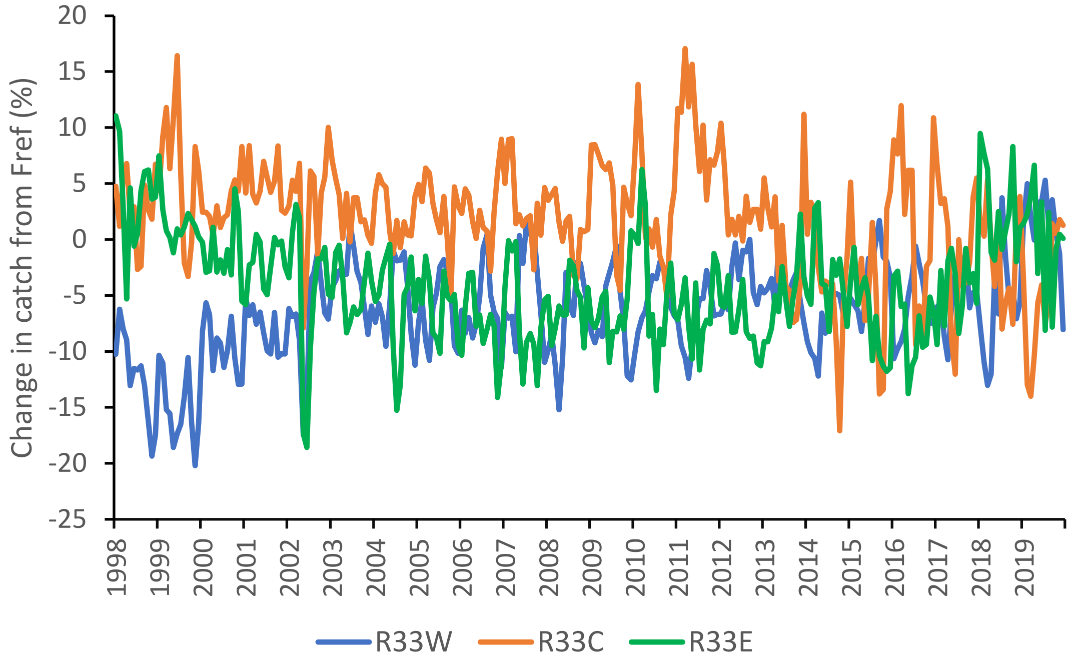
Supplementary Table 4. Average contribution of the PIPA to the skipjack and bigeye tuna stocks under unexploited conditions in the Pacific, and western and central Pacific Ocean (WCPO) at different life stages. Estimated over the period 1998-2019 for the SEAPODYM simulation F0. Larvae refer to tuna <1 month of age; recruits three months of age, and adults greater than approximately one year (skipjack tuna) and approximately three years (bigeye tuna) of age.

PIPA contribution	**Larvae**		**Recruits**		**Adult**		**Total Biomass**	
	All Pacific	WCPO	All Pacific	WCPO	All Pacific	WCPO	All Pacific	WCPO
Skipjack tuna	0.54%	1.33%	0.50%	1.21%	0.49%	1.13%	0.49%	1.12%
Bigeye tuna	0.49%	0.90%	0.54%	1.00%	0.46%	0.80%	0.48%	0.84%

6 Impact of hypothetical 33% spatial closures on main fishery catches



Supplementary Figure 5. Time series of relative changes in tropical purse seine (S5 and S7) skipjack tuna catches from the observed fishing activity (Fref) for retrospective large closures of approximately 33% of the western and central Pacific Ocean in the west (R33W), central (R33C) and eastern areas (R33E). Catch-per-unit-effort shows the same changes as total effort is conserved in the simulations. See Figure 1 of the main text for a description of the areas.



Supplementary Figure 6. Time series of relative changes in longline (L1 – L11) bigeye tuna catches from the observed fishing activity (Fref) for retrospective large closures of approximately 33% of the western and central Pacific Ocean in the west (R33W), central (R33C) and eastern areas (R33E). Catch-per-unit-effort shows the same changes as total effort is conserved in the simulations. See Figure 1 of the main text for a description of the areas.