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Supplementary Materials for

Stock assessment models overstate sustainability of the world's fisheries

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Materials and Methods
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References

Other Supplementary Material for this manuscript includes the following:

MDAR Reproducibility Checklist

Materials and Methods

Datasets

Three datasets with modeled hindcast trends in spawning stock biomass (B) were analysed: historical (version 1.0, downloaded 15 Aug 2011) and recent (version 4.46, downloaded on 2 July 2020) extracts from the RAM Legacy database—the global repository of fisheries data (*42*); the SMART compilation of data for USA fisheries (*37*); and modeled annual biomass trends for 16 stocks investigated in the Australian South East Scalefish and Shark Fishery retrospective analysis (data plotted as Fig. 1 of Punt et al. (*7*)). Modeled data were excluded when expressed in units not convertible to metric tonnes (e.g. number of eggs produced), and when sequential assessments for each stock were not independent (i.e. annual biomass values described for older assessments were identical to values in the same years in the most recent assessment).

Where time series for a particular stock were covered in multiple databases, duplicate RAM 2011 records were first excluded, then RAM 2020 records, while retaining all relevant SMART and SESSF data. Retrospective analyses require at least two time series, consequently stocks with a most recent assessment but no older assessment could not be used. Years prior to 1920 (8.7% of total available data) were excluded from analysis to allow focus on the past century of change.

Limit Reference Points

Our study was directed at stock depletion—the percentage of unfished biomass remaining in the wild after reduction through fishing pressure. Data for unfished biomass (B_0) were unavailable for most fisheries. The maximum biomass reported in the fishery in any year (B_{max}) was therefore used as proxy B_0 because it approximated the maximum stock biomass known (Fig. S1).

While a variety of reference points related to stock depletion have been used as benchmarks for target stock size, overfishing and recruitment impairment (e.g. *11, 12, 43*), we applied a depletion ratio (B/B_{max}) of 0.4 as the threshold for overfishing. We based this value on Thorson et al's (*14*) conclusion that maximum sustainable yield (MSY) is produced at $B/B_0 = 0.4$ on average, and evidence that total stock productivity and economic yield are higher above than below this level based on meta-analyses of hundreds of fisheries (*31, 44*). Depleting stocks below the biomass at MSY is difficult to justify due to potential losses in catch, economic returns, and environmental sustainability. Maximum economic yield, for example, is achieved at B/B_{max} reference points that are higher than the biomass supporting MSY, because greater catch per unit effort and lower operating costs are achieved (*45*). Moreover, once a stock is fished below the biomass supporting MSY, fishers often resist management action aimed at stock recovery due to concerns about short-term reductions in income while stocks recover (*17*). $B/B_0 < 0.1$ is widely applied as a benchmark to signify collapsed fisheries (e.g. *16, 46*). Declining recruitment is commonly assumed when $B/B_0 < 0.2$ (*18, 47, 48*).

Sustainability status (Fig. 2) was assessed using depletion estimates (B/B_{max}) from the final year of the most recent assessment with two exceptions. For assessment of variation in bias with stock depletion using GLMMs (Figures 4 and 5), we used the depletion estimate from the most recent assessment for the final year of the historical assessment rather than the most recent assessment because we expected the true status to have influenced decisions at the time of the older assessment, not the future status in the most recent assessment. For assessment of year-by-year bias within stocks (Fig. 3), overfished stocks were additionally identified using B/B_{max} values five years prior to the final year of historical assessments to avoid potential issues of circularity (Fig. S3). Little difference was found in plots regardless of whether calculated using B/B_{max} values in the final year or five years earlier (Figures 3, S3).

Analysis of bias

The magnitude of bias in stock biomass (ΔB) in stock estimates was assessed through comparison of historical stock biomass values with the most recent assessment (MRA). ΔB was estimated using the log response ratio: $\ln \left({B'}_F / B_F \right)$; where F is the final year of an assessment, B'_F is the final biomass in the older assessment, and B_F is the biomass reported in the MRA for year F (Fig. 1). Biomass estimates are most uncertain for the final year biomass. The MRA was chosen as the best reference yardstick available for true stock biomass because it encompasses all information from earlier assessments, additional data from more recent years, potentially improved modeling, and correction of any errors detected in previous models. Nevertheless, the MRA may also include substantial bias, as shown by the considerable variability among hindcast assessments (Fig. 1). Bias statistics were exponentially back-converted as a geometric mean ratio.

The same approach was used to calculate ΔB_{max} and $\Delta B/B_{max}$, where maximum stock biomass (B_{max}) was calculated for each assessment as B for the year with largest estimate. Depletion estimates relative to B_{max} varied greatly between different regional assessment groups, and exhibited large spatial differences in stock trajectories through time (Supplementary Appendix, Table S1).

Covariate relationships with bias were assessed using the generalized linear mixed model (GLMM):

$\ln (\Delta B/B_{max})$ ~ depletion + assessment age + SST trend + value + Mean SST + duration + assessment age × depletion + value × depletion + clupeoid + (1|stock name).

The same model structure was also fit with ΔB and ΔB_{max} as the response variable.

This model includes the following fixed factors: 1. Depletion: $\mathrm{B_F^{MRA}} / \mathrm{B_{max}^{MRA}}$ ($= \mathrm{B/B_{max}^{MRA}}$) from the MRA in the final year (F) of each older assessment; 2. Assessment age: years between the final year of a stock assessment and the final year of the MRA; 3. SST trend: regional warming trend over 50 year period leading to stock assessment year (°C/decade); 4. Stock value: stock total value (B tonnes × unit bench price per tonne), where unit price was calculated using FAO data on US$/tonne in 2018 for different species groups from (Table II, World Fishery Production *49*); 5. Mean SST: regional mean sea surface temperature (°C); 6. Duration: length of data series (years); 7. Clupeoids: small pelagic fishes, defined as the FAO group "Herrings, sardines, anchovies" (*49*) versus other FAO groups combined. 8. Interaction: assessment age × depletion; 9. Interaction: value × depletion. Stock name (species name + region name, Table S1) was included as a random effect because of non-independence for stocks assessed in multiple years. Mean SST (°C) was calculated using an average for the 5 years spanning 2015 to 2019, and SST trend calculated as the linear relationship between mean temperature and year over the 50-year period to year of assessment, for mean monthly data provided by the Hadley Centre Sea Surface Temperature (HADISST) data set (http://www.metoffice.gov.uk/hadobs/hadisst/data/HadISST_sst.nc.gz) (*50*). For these calculations the closest lat×long position in the HADISST dataset was matched for each stock centroid location. NaN and -1000 values were removed. The 50 year trend was the slope estimate for SST~ year, accounting for the average seasonal fit across months, using the bicubic function in GAM, as described in: https://fromthebottomoftheheap.net/2014/05/09/modeling-seasonal-data-with-gam/. We also tested for sensitivity associated with the HADISST by running models with BioOracle SSTmeanBO (*51*) to ensure our results were not reliant on idiosyncratic values returned by any one SST database. The two temperature datasets showed almost 1:1 correspondence ($R^2 = 0.99$).

Initial model runs tested the probability that the first six factors interacted with depletion (B/B_{max}). The interactions assessment age × depletion and value × depletion provided a much improved model fit (lowest Watanabe-Akaike information criteria statistic: WAIC (*21*)) when added to the other six fixed effects (Supplementary Appendix, Table S2). The final model included linear interactions of assessment age and value with depletion and all main effects.

Covariate models were fitted by Bayesian Regression Modeling using the Stan R package, assuming a Gaussian distribution for the response (*52*, *53*). Estimation used 4,000 samples in each of three chains, started at random initial values. Convergence was confirmed with the Rhat statistic and by ensuring the effective sample sizes were in the 1,000s. Marginal effects for each covariate were calculated with 95% credible intervals and predicted effects were calculated with 95% credible intervals conditional on the stock random effect set to zero. We plotted predictions against observations to confirm the linear assumption and that there were no outliers with undue influence (Fig. S8). For $\Delta B/B_{max}$ we initially fit a model with two-way interactions between depletion level and all other covariates. We then simplified that model stepwise with the WAIC statistic (*22*). We finally fit the simplified model to all three bias variables.

We assessed whether the strong depletion × assessment age interaction was driven by improvements in stock modeling protocols through time by rerunning the analysis described above following replacement of the assessment age data (years between stock assessment and most recent assessment) with most recent assessment calendar year.

Estimation of bias in hindcast annual sequences for B/B_{max} and trends

For each stock assessment, we first calculated B/B_{max} for each hindcast year, and also the *trend* for each pair of years (calculated as the log gradient, the difference of logged B/B_{max} values for successive years). We then calculated the logged response ratio for B/B_{max} and trend relative to data for the same year in most recent assessments, thus deriving an annual within-stock bias sequence extending back from the assessment year (=0). 'Years hindcast' was defined as the assessment year minus the time-series year. We then developed curves showing the median annual bias and trend bias, averaged across all assessments, for two status groups: sustainable ($B/B_{max} \geq 0.4$) or overfished stocks ($B/B_{max} < 0.4$). B/B_{max} was additionally assessed five years prior to the final assessment year to avoid any confounding between final year trend and status. We used the median because of outliers in year-by-year trends that exerted a disproportionate influence on the mean. Finally, we fit generalized additive models (GAMs) to each annual sequence, and plotted the mean ±95% confidence intervals. GAMs were fit with thin plate splines.

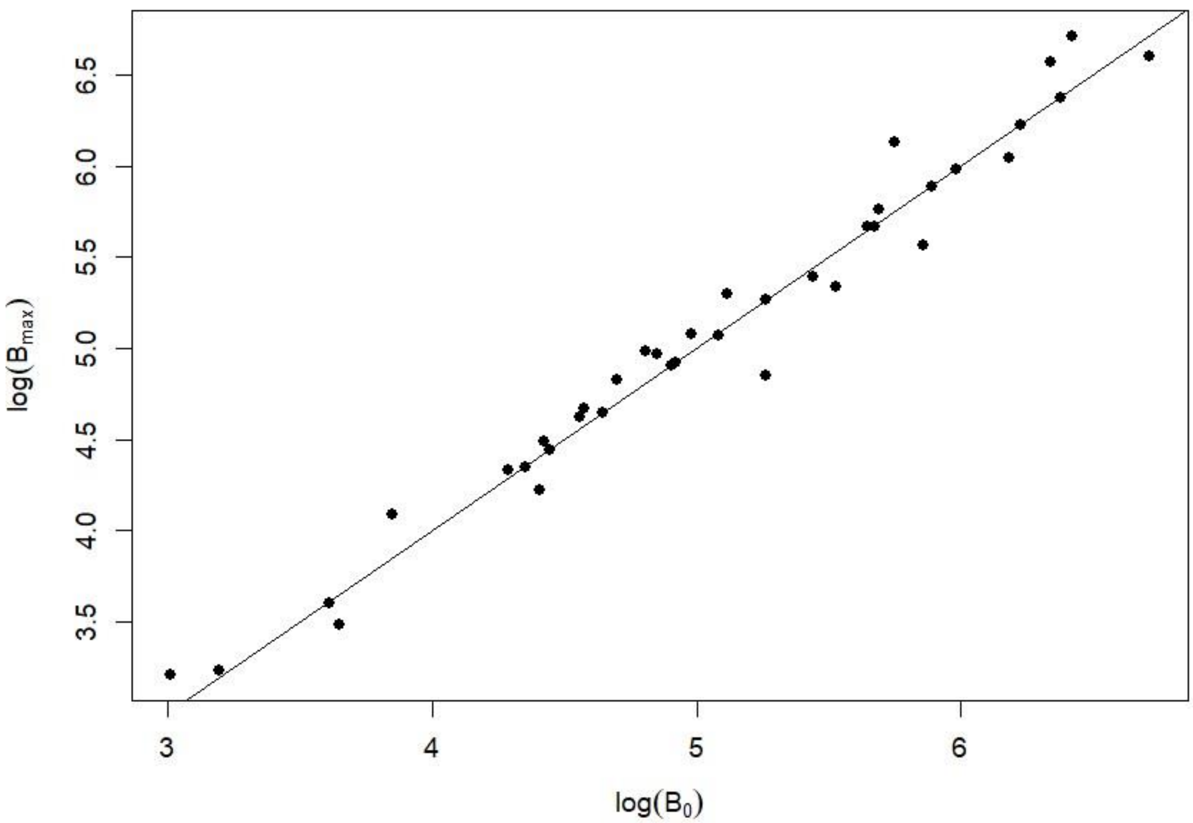

Fig. S1.
Relationship between modeled spawning stock biomass for unfished stock (B_0) and the maximum stock size in any year (B_{max}). Modeled values for unfished biomass B_0, which is typically used as the reference condition in fisheries models, were only available through the RAM database (*42*) for 38 of the stocks investigated here. On average, the RAM B_0 estimates were 5.8% lower than our calculated B_{max} values. $R^2 = 0.97$. Solid black line depicts $B_0 = B_{max}$.

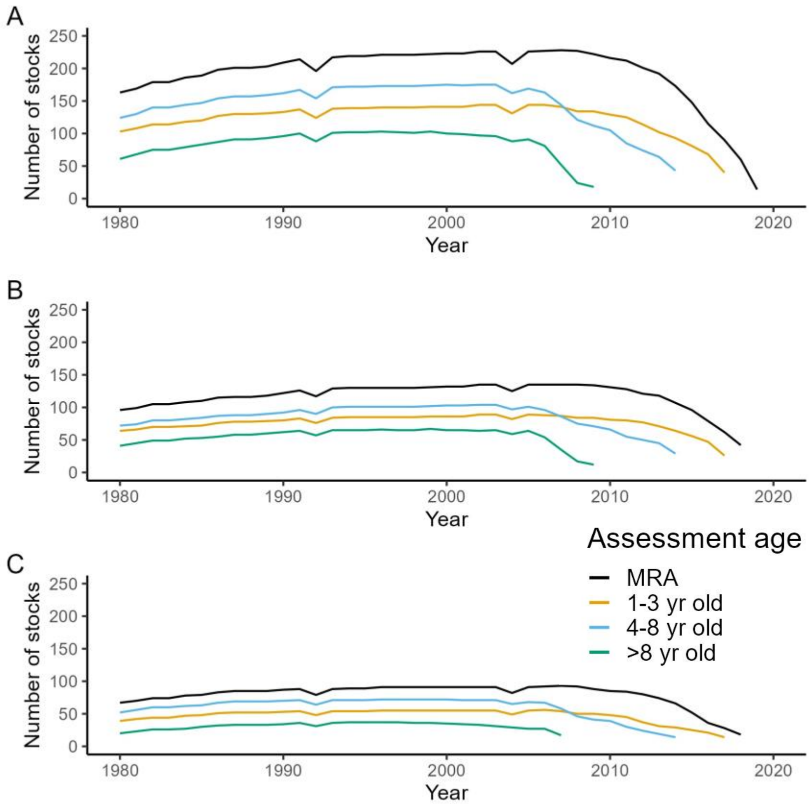

Fig. S2.

Number of stocks considered in different years. Numbers of assessments for each time series curve shown in Fig. 2. **(A)**. For all 230 stocks investigated. **(B)**. For the subset of 162 (70%) stocks with B/B_{max} in most recent assessment at sustainable levels (>0.4). **(C)**. For the subset of 68 (30%) overfished stocks ($B/B_{max} \leq 0.4$).

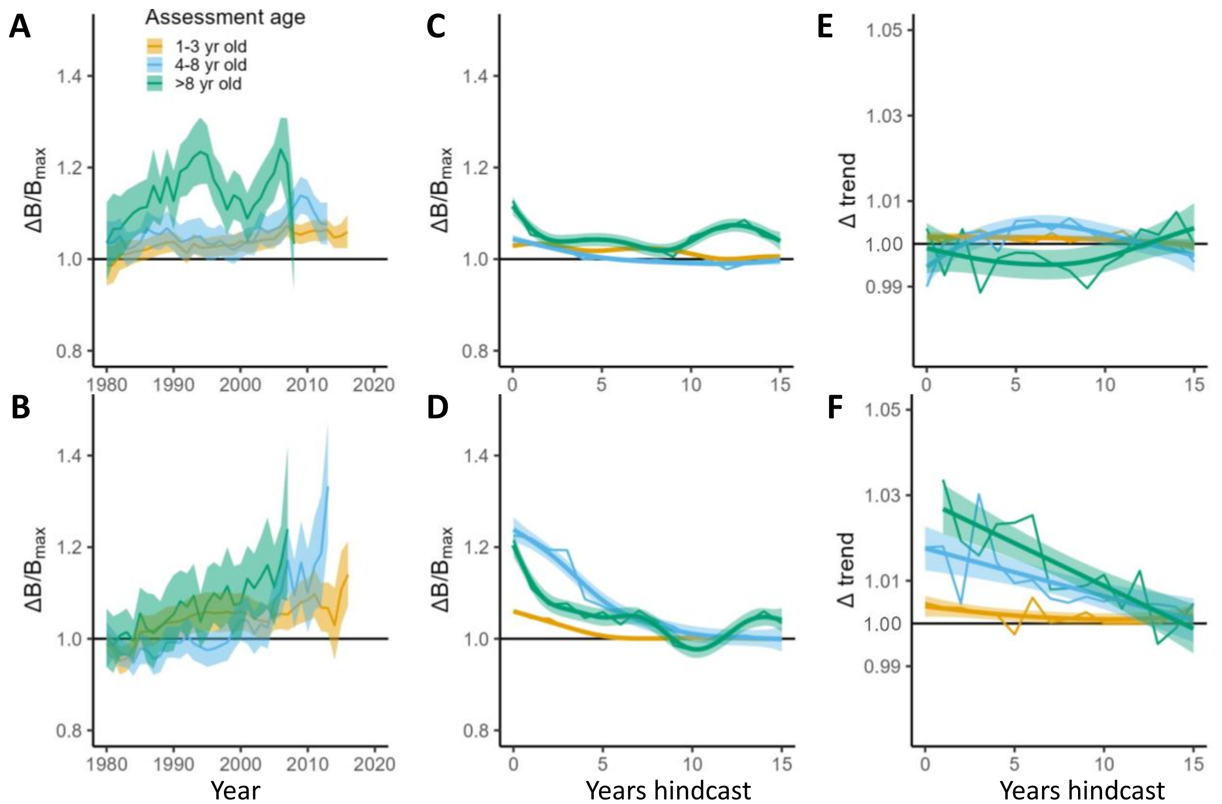

Fig. S3.

Variation through time in depletion and trend ratios, where old assessment estimates are divided by the most recent modeled hindcast estimate for the same year. Stock status (sustainable $B/B_{max} > 0.4$, or overfished $B/B_{max} < 0.4$) was categorized in the final assessment year. **(A).** Mean (± 1 SE) depletion bias ratio (i.e., log ratio of B/B_{max}, exponentially back-transformed to multiplicative scale) for sustainable stocks. **(B)**. Mean (± 1 SE) depletion bias ratio for overfished stocks. **(C)** Median (± 95% CI) depletion bias ratio versus number of years between final stock assessment year and most recent assessment year ('years hindcast') for sustainable stocks. **(D)** Median (± 95% CI) depletion bias ratio versus number of years of hindcast data for overfished stocks. **(E)** Median (± 95% CI) trend bias ratio (i.e. the gradient difference in logged B/B_{max} values for successive years) versus number of years of hindcast data for sustainable stocks. **(F)** Median (± 95% CI) trend bias ratio versus number of years of hindcast data for overfished stocks.

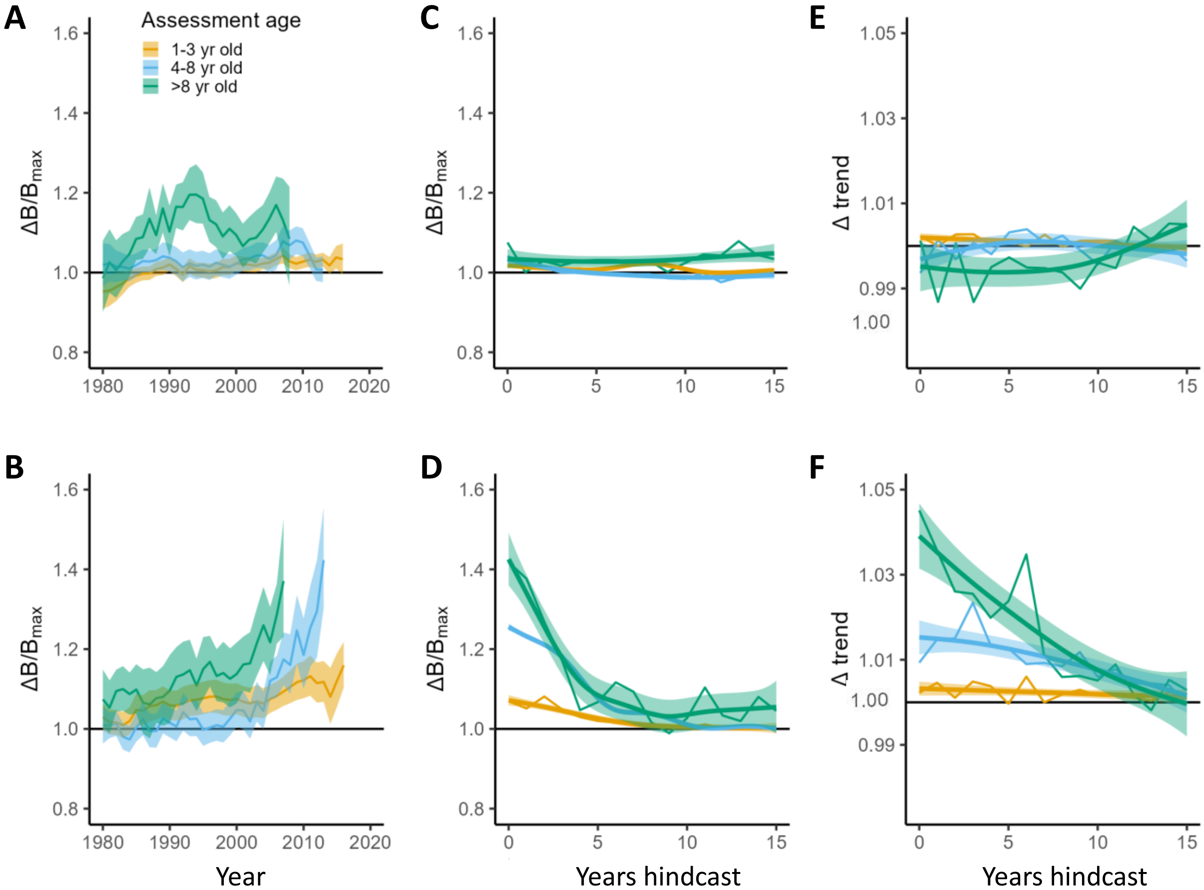

Fig. S4.

Variation through time in depletion and trend ratios, where stock status was categorized five years prior to the final assessment year. (A). Mean (± 1 SE) depletion ratio (i.e., depletion estimate in old stock assessment divided by estimate for the most recent assessment in the same year) for sustainable stocks. **(B)**. Mean (± 1 SE) depletion ratio for overfished stocks. **(C)** Variation in depletion bias versus number of years of hindcast data for sustainable stocks. Shading depicts 95% confidence intervals derived from general additive models. **(D)** Variation in depletion bias versus number of years of hindcast data for overfished stocks. **(E)** Variation in trend bias (i.e. the gradient difference in logged B/B_{max} values for successive years) versus number of years of hindcast data for sustainable stocks. **(F)** Variation in trend bias versus number of years of hindcast data for overfished stocks. Shading depicts 95% confidence intervals derived from generalized additive models.

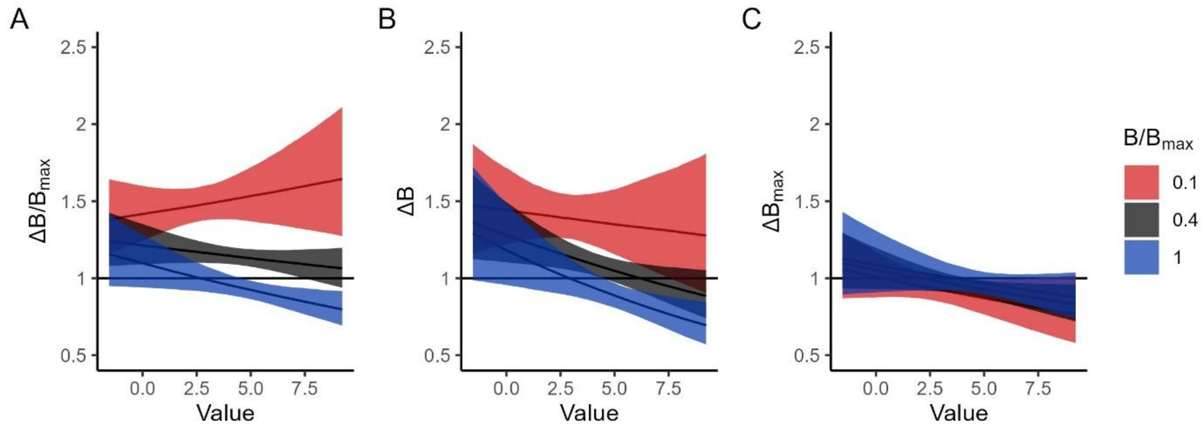

Fig. S5.
Relationships between depletion bias and stock value. Generalized log-linear mixed model output depicts relationships between bias and value, with other covariates set to 0. **(A)** $\Delta B/B_{max}$. **(B)** ΔB. **(C).** ΔB_{max}. Separate curves are modeled for sustainable stocks with no depletion ($B/B_{max} = 1$), stocks at the overfished threshold ($B/B_{max} = 0.4$), and stocks at the collapsed threshold ($B/B_{max} = 0.1$). Shaded areas indicate 95% credible intervals.

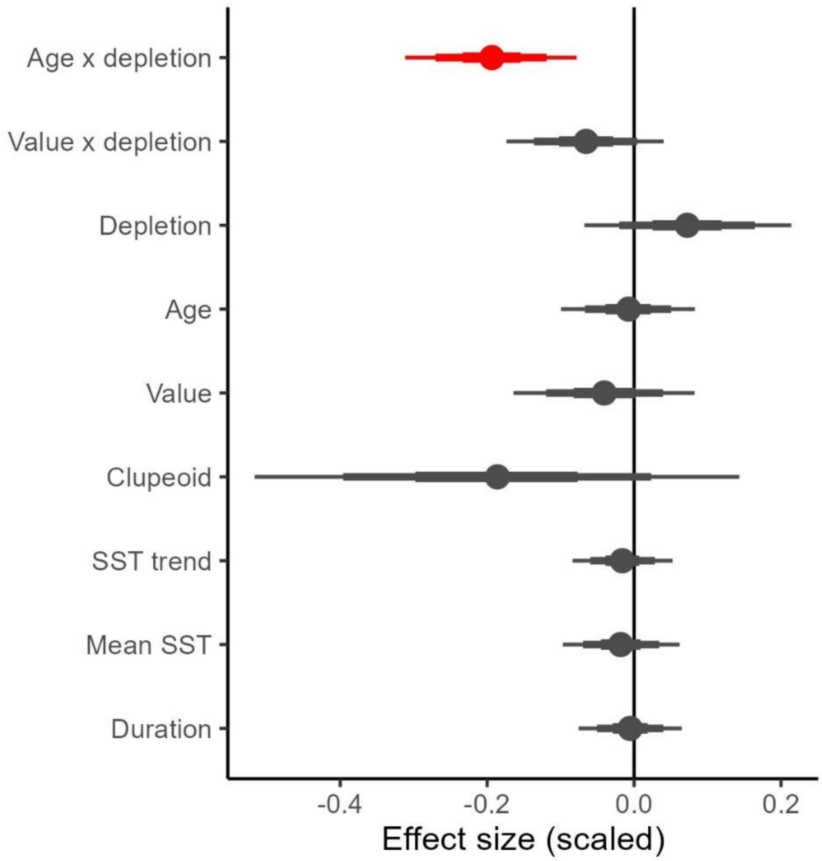

Fig. S6.
Varying influences of covariates on bias in $\Delta B/B_{max}$ in stock model output, using the subset of data to 2010. Coefficient estimates calculated from generalized linear mixed-effect models relating bias Δ to seven covariates plus the interactions *assessment age* × *depletion* and *value* × *depletion*. Error bars indicate 95% credible intervals, highlighting a significant effect when not overlapping 0 (marked in red).

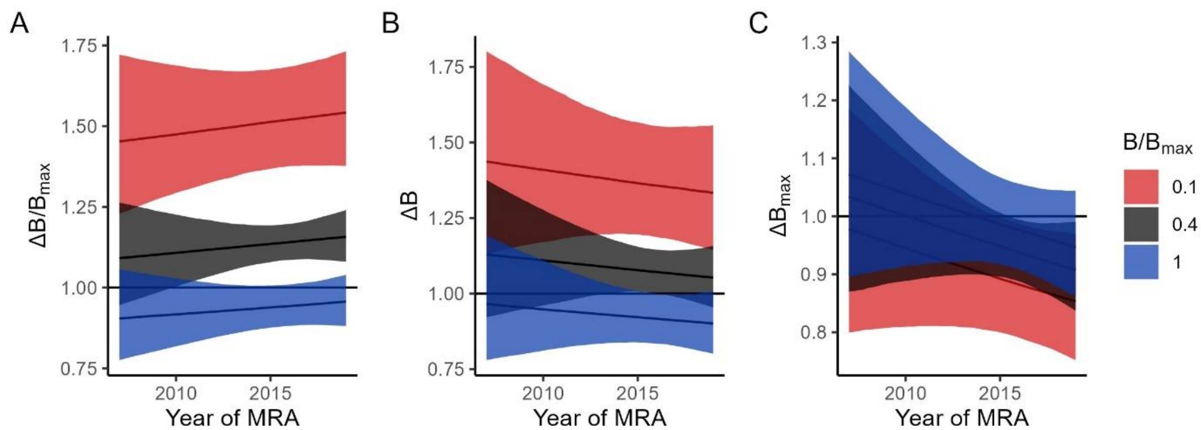

Fig. S7.
Depletion bias has not declined in recent calendar years. Generalized log-linear mixed model output depicts relationships between $\Delta B/B_{max}$, ΔB, ΔB_{max} and calendar year of most recent assessment (MRA), with other covariates set to 0.

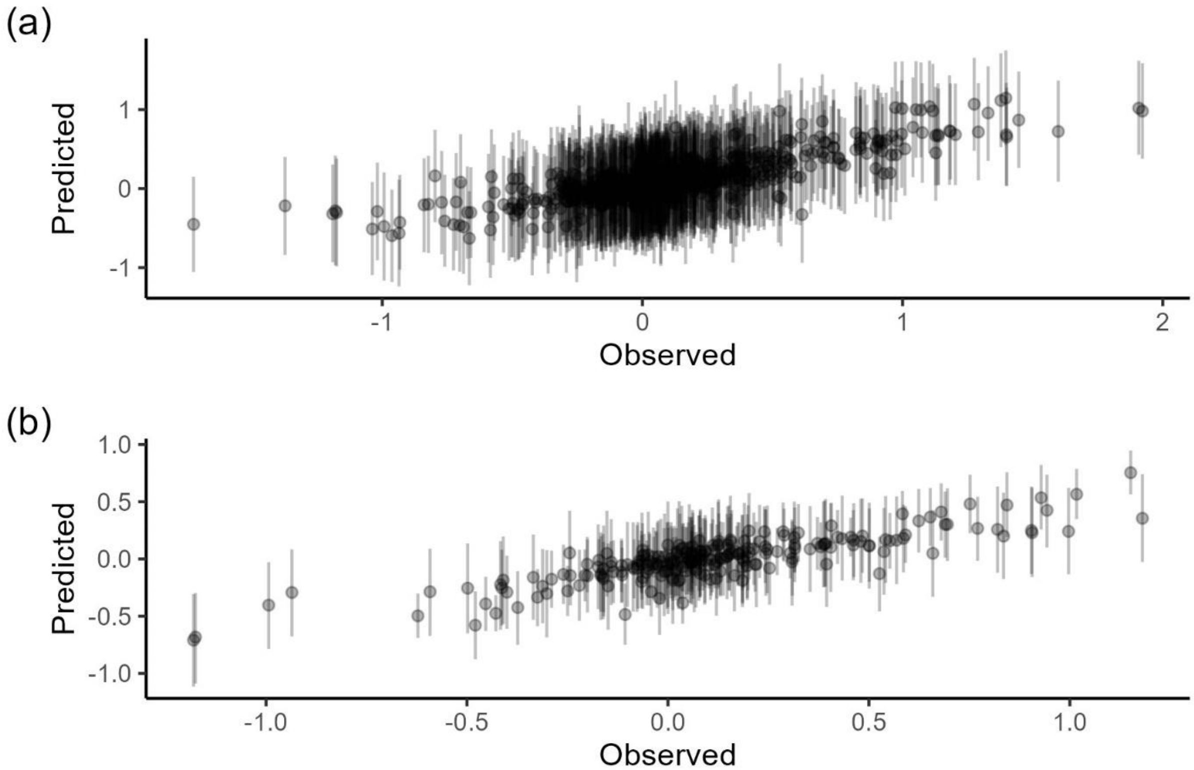

Fig. S8.
Observation versus predictions for bias in the depletion ratio ln(ΔB/B_{max}). Separate relationships against stock level random effect estimates are plotted for **(A)** all assessments and **(B)** stock mean biases. SE bars shown.

Species	Region	National group	Year	Years	N	MRA B/B_{max}	Mean $\Delta B/B_{max}$	Mean ΔB	Mean ΔB_{max}	SD $\Delta B/B_{max}$	SD ΔB	SD ΔB_{max}
Argentine anchoita	Northern Argentina	Argentina[1]	1990	26	2	0.51	0.15	-0.01	-0.16	0.01	0.24	0.01
Argentine anchoita	Southern Argentina	Argentina[1]	1990	25	1	0.69	0.05	0.19	0.14	#	#	#
Argentine hake	Northern Argentina	Argentina[1]	1986	28	2	0.2	0.07	0.04	-0.03	0.11	0.01	0.11
Argentine hake	Southern Argentina	Argentina[1]	1990	24	1	0.92	-0.1	-0.38	-0.28	#	#	#
Patagonian grenadier	Southern Argentina	Argentina[1]	1985	30	1	0.35	-0.05	0.45	0.5	#	#	#
Southern blue whiting	Southern Argentina	Argentina[1]	1987	27	1	0.24	0.9	0.97	0.07	#	#	#
Bight redfish	SE Australia	Australia[4]	1960	54	5	0.6	0.29	1.46	1.17	0.61	0.5	0.61
Blue Grenadier	SE Australia	Australia[4]	1979	31	8	0.65	-0.62	-0.41	0.21	0.38	0.17	0.38
Blue warehou east	SE Australia	Australia[4]	1986	22	3	0.05	0.59	0.94	0.36	0.78	0.38	0.78
Blue warehou west	SW Australia	Australia[4]	1986	22	3	0.15	-0.48	0.16	0.63	0.4	0.33	0.4
Deepwater Flathead	SE Australia	Australia[4]	1980	35	5	0.45	0.2	0.41	0.21	0.41	0.52	0.41
Eastern gemfish	SE Australia	Australia[4]	1968	40	2	0.15	0.12	-0.07	-0.19	0.17	0.03	0.17
Gummy shark (BS)	Bass Strait	Australia[4]	1927	89	4	0.53	-0.07	-0.25	-0.18	0.93	0.53	0.93
Gummy shark (SA)	South Australia	Australia[4]	1927	89	4	0.63	-0.24	-0.68	-0.43	1.05	0.54	1.05
Gummy shark (TAS)	Tasmania	Australia[4]	1927	89	1	0.75	0.08	0.15	0.07	#	#	#
Morwong East	SE Australia	Australia[4]	1920	94	6	0.09	0.37	0.2	-0.18	0.34	0.11	0.34
Morwong West	SW Australia	Australia[4]	1986	28	3	0.63	0.17	0.54	0.37	0.17	0.16	0.17
Orange Roughy	SE Australia	Australia[4]	1980	33	2	0.17	-0.02	0.07	0.09	0.38	0.03	0.38
Pink Ling East	SE Australia	Australia[4]	1970	43	5	0.18	0.42	0.24	-0.18	0.07	0.11	0.07
Pink Ling West	SW Australia	Australia[4]	1970	43	5	0.41	0.09	0.2	0.11	0.31	0.2	0.31
Redfish	SE Australia	Australia[4]	1976	37	1	0.1	0.84	1.68	0.85	#	#	#
School shark	SE Australia	Australia[4]	1927	81	3	0.1	0.69	1.39	0.7	0.7	0.14	0.7
School Whiting	SE Australia	Australia[4]	1947	61	4	0.44	0.68	0.33	-0.35	0.52	0.44	0.52
Silver Warehou	SE Australia	Australia[4]	1980	34	6	0.28	-0.25	-0.54	-0.29	0.49	0.28	0.49
Tiger flathead	SE Australia	Australia[4]	1920	95	5	0.41	0.16	0.13	-0.03	0.21	0.1	0.21
Atlantic cod	Southern Gulf	Canada[2]	1971	44	1	0.08	0.39	0.38	-0.02	#	#	#
Atlantic cod	Southern Labrador	Canada[2]	1962	52	1	0.12	0.01	0.01	0	#	#	#
Herring	Gulf St Lawrence (Fall)	Canada[2]	1978	36	1	0.31	0.25	0.5	0.26	#	#	#
Herring	S Gulf St Lawrence (Spring)	Canada[2]	1978	36	1	0.19	1	1.07	0.07	#	#	#

Mackerel	Northwest Atlantic	Canada[2]	1968	45	1	0.02	1.18	0.76	-0.42	#	#	#
Pacific herring	Central Coast	Canada[1]	1951	64	1	0.37	0.22	0.42	0.2	#	#	#
Pacific herring	Prince Rupert District	Canada[2]	1951	64	1	0.22	0.19	0.03	-0.16	#	#	#
Pacific herring	Queen Charlotte Islands	Canada[2]	1951	64	1	0.15	0.91	0.48	-0.42	#	#	#
Pacific herring	Strait of Georgia	Canada[2]	1951	64	1	0.93	-0.06	0.12	0.18	#	#	#
Pacific herring	West Vancouver Island	Canada[2]	1951	64	1	0.14	-1.18	-0.7	0.48	#	#	#
Rock sole	Hecate Strait	Canada[2]	1945	69	1	0.71	-0.17	-1.15	-0.99	#	#	#
Winter flounder	S Gulf St Lawrence	Canada[2]	1973	39	1	0.23	-0.01	0	0	#	#	#
Albacore tuna	Pacific Ocean	Multinational Tuna[1]	1960	53	1	0.47	-0.99	-0.74	0.25	#	#	#
Atlantic bluefin	Eastern Atlantic	Multinational Tuna[1]	1968	47	2	1	0.01	-0.36	-0.37	0.78	0.43	0.78
Atlantic bluefin	Western Atlantic	Multinational Tuna[1]	1974	41	3	0.61	0.02	0.43	0.41	0.48	0.05	0.48
Bigeye tuna	Indian Ocean	Multinational Tuna[1]	1974	40	2	0.41	-0.41	-0.43	-0.02	0.29	0.38	0.29
Skipjack tuna	Central Western Pacific Ocean	Multinational Tuna[1]	1972	43	1	0.87	0.16	0.06	-0.09	#	#	#
Yellowfin tuna	Central Western Pacific Ocean	Multinational Tuna[1]	1952	63	1	0.23	0.04	-0.34	-0.38	#	#	#
Atlantic cod	North-East Arctic	ICES Arctic[2]	1946	72	6	0.56	-0.06	-0.29	-0.23	0.23	0.13	0.23
Capelin	Barents Sea	ICES Arctic[1]	1972	45	1	0.44	0.31	-1.5	-1.81	#	#	#
Golden redfish	North-East Arctic	ICES Arctic[1]	1990	27	2	0.33	-0.4	-0.32	0.08	0.09	0.07	0.09
Greenland halibut	North-East Arctic	ICES Arctic[1]	1992	22	2	1	0.06	-2.51	-2.57	0.35	0.32	0.35
Haddock	North-East Arctic	ICES Arctic[2]	1950	67	5	0.8	-0.2	-0.42	-0.22	0.55	0.35	0.55
Pollock	North-East Arctic	ICES Arctic[1]	1960	58	6	0.64	0.02	0.04	0.02	0.24	0.12	0.24
Atlantic cod	Eastern Baltic	ICES Baltic[1]	1966	47	2	0.28	0.25	0.33	0.08	0.29	0	0.29
Atlantic cod	Kattegat	ICES Baltic[1]	1971	41	1	0.07	-0.15	0.22	0.37	#	#	#
Atlantic cod	Western Baltic	ICES Baltic[1]	1994	24	7	0.7	0.38	0.46	0.08	0.49	0.09	0.49
Herring	Bothnian Bay	ICES Baltic[1]	1980	30	1	0.21	0.07	0.11	0.05	#	#	#
Herring	Bothnian Sea	ICES Baltic[1]	1973	43	5	1	0.29	0.03	-0.26	0.38	0.41	0.38
Herring	Eastern Baltic	ICES Baltic[1]	1974	37	1	0.3	0.57	0.56	-0.01	#	#	#
Herring	Gulf of Riga	ICES Baltic[1]	1977	41	7	0.7	-0.12	-0.18	-0.06	0.13	0.02	0.13
Atlantic cod	Europe non EU	ICES North-West[1]	1959	59	7	0.28	0.13	0.13	0	0.25	0	0.25
Atlantic cod	Iceland Grounds	ICES North-West[1]	1955	63	7	0.69	0.02	0.04	0.02	0.08	0.07	0.08
Pollock	Europe non EU	ICES North-West[1]	1961	57	7	0.43	0.58	0.49	-0.1	0.25	0.05	0.25
Haddock	Faroe Plateau	ICES North-West[1]	1957	61	7	0.27	0.27	0.32	0.04	0.12	0.04	0.12

Haddock	Iceland Grounds	ICES North-West[1]	1979	38	6	0.42	-0.07	-0.07	0	0.06	0	0.06
Herring	Europe non EU	ICES North-West[1]	1987	31	7	0.36	-0.21	-0.03	0.17	0.33	0.09	0.33
Anchovy	Bay of Biscay	ICES Others[1]	1987	30	4	0.77	0.06	0.06	0	0.25	0.14	0.25
Blue whiting	Northeast Atlantic	ICES Others[1]	1981	37	6	0.86	0.11	0.14	0.03	0.21	0.02	0.21
Fourspotted megrim	ICES 8c-9a	ICES Others[1]	1986	31	6	1	0.13	0.03	-0.1	0.19	0.08	0.19
Hake	ICES 3a-4-6-7-8abd	ICES Others[1]	1978	40	7	0.88	0.41	0.05	-0.35	0.59	0.33	0.59
Hake	ICES 8c-9a	ICES Others[1]	1982	36	7	0.52	0.32	0.33	0.01	0.16	0.05	0.16
Herring	ICES 22-24-3a	ICES Others[1]	1991	27	7	0.35	0.17	0.22	0.05	0.13	0.02	0.13
Herring	ICES 5a-7bc	ICES Others[1]	1957	61	6	0.12	-0.45	-0.9	-0.45	1.44	0.49	1.44
Herring	Irish Sea	ICES Others[1]	1980	38	6	0.82	-0.05	-0.33	-0.29	0.3	0.15	0.3
Herring	West of Scotland	ICES Others[1]	1957	56	2	0.22	-0.16	-0.16	0	0.17	0.04	0.17
Mackerel	European Union	ICES Others[1]	1980	37	5	0.79	0.13	0.08	-0.05	0.08	0.28	0.08
Megrim	ICES 8c-9a	ICES Others[1]	1986	32	7	1	0.08	0.07	-0.01	0.24	0.03	0.24
Sprat	European Union	ICES Others[1]	1974	44	5	0.74	0.32	0.29	-0.03	0.22	0.09	0.22
Atlantic cod	Irish Sea	ICES Celtic Seas[1]	1968	49	6	0.5	-0.04	-0.09	-0.05	0.3	0.02	0.3
Atlantic cod	West of	ICES Celtic Seas[1]	1981	36	6	0.06	0.19	0.18	-0.01	0.42	0.02	0.42
Common sole	Celtic Sea	ICES Celtic Seas[1]	1971	47	7	0.34	0.12	0.15	0.03	0.13	0.03	0.13
Common sole	Eastern English	ICES Celtic Seas[1]	1982	36	7	0.62	-0.01	-0.44	-0.44	0.37	0.2	0.37
Common sole	Irish Sea	ICES Celtic Seas[1]	1970	48	7	0.33	0.03	0.02	-0.01	0.19	0.04	0.19
Common sole	North Sea	ICES Celtic Seas[1]	1957	61	7	0.48	0.1	0.09	-0.01	0.07	0.03	0.07
Common sole	Western English	ICES Celtic Seas[1]	1969	49	7	0.74	-0.02	-0.02	0	0.16	0.01	0.16
European plaice	Celtic Sea	ICES Celtic Seas[1]	1993	17	1	0.83	-0.16	-0.32	-0.16	#	#	#
European plaice	Eastern English	ICES Celtic Seas[1]	1980	38	5	0.83	0.19	-0.34	-0.53	0.81	0.97	0.81
European plaice	Irish Sea	ICES Celtic Seas[1]	1981	37	3	1	0.62	0.39	-0.23	0.53	0.56	0.53
European plaice	North Sea	ICES Celtic Seas[1]	1957	61	7	1	0.24	-0.07	-0.31	0.19	0.32	0.19
European plaice	Western English	ICES Celtic Seas[1]	1980	34	3	1	0.01	-0.08	-0.09	0.14	0.14	0.14
Haddock	Irish Sea	ICES Celtic Seas[2]	1993	24	1	1	0.24	0.03	-0.21	#	#	#
Haddock	Rockall Bank	ICES Celtic Seas[1]	1991	26	6	0.63	0.3	0.33	0.03	0.32	0.01	0.32
Haddock	West of Scotland	ICES Celtic Seas[1]	1978	35	2	0.35	-0.22	-0.2	0.02	0.22	0.03	0.22
Whiting	Celtic Sea	ICES Celtic Seas[2]	1999	18	6	0.67	0.07	-0.19	-0.26	0.13	0.26	0.13
Whiting	West of Scotland	ICES Celtic Seas[1]	1981	36	5	0.13	0.55	0.54	-0.02	0.42	0.02	0.42

Atlantic cod	Canada East Coast	Other[1]	1978	37	2	0.17	0.17	0.03	-0.13	0.2	0.2	0.2
Chilean jack mackerel	Chilean EEZ	Other[2]	1970	45	1	0.2	-1.18	-0.98	0.2	#	#	#
Pacific halibut	US Alaska	Other[1]	1996	18	1	0.34	0.82	0.72	-0.1	#	#	#
Peruvian anchoveta	North-Central Peruvian coast	Other[1]	1962	46	1	0.57	0.13	0.44	0.32	#	#	#
Walleye pollock	Northern Sea of Okhotsk	Other[2]	1963	51	1	0.64	-0.01	-0.01	0	#	#	#
Australian salmon	New Zealand	New Zealand[1]	1929	84	1	0.62	-0.34	-0.27	0.06	#	#	#
Hoki	Eastern New Zealand	New Zealand[1]	1970	45	2	0.58	0.11	0.16	0.05	0.48	0.17	0.48
Hoki	Western New Zealand	New Zealand[1]	1970	45	2	0.44	-0.31	-0.21	0.1	0.02	0.16	0.02
Ling	New Zealand Areas LIN 72	New Zealand[1]	1968	42	1	0.47	0.05	0.13	0.07	#	#	#
Ling	New Zealand Areas LIN 7WC	New Zealand[1]	1968	44	1	0.63	0.11	0.2	0.09	#	#	#
Orange Roughy	New Zealand	New Zealand[1]	1920	94	2	0.11	0.5	0.31	-0.19	0.86	0.03	0.86
Paua	New Zealand Area PAU 5B	New Zealand[1]	1965	48	1	0.44	0.39	0.21	-0.18	#	#	#
Paua	New Zealand Area PAU 5D	New Zealand[1]	1965	47	1	0.35	-0.5	-0.67	-0.17	#	#	#
Paua	New Zealand Area PAU 7	New Zealand[1]	1965	50	2	0.18	0.46	0.4	-0.06	0.33	0.04	0.33
Smooth oreo	Chatham Rise	New Zealand[1]	1955	58	2	0.3	0.02	0.42	0.41	0.25	0.16	0.25
Smooth oreo	West end	New Zealand[1]	1965	44	1	0.35	0.06	0.06	0	#	#	#
Southern blue whiting	New Zealand	New Zealand[1]	1977	36	2	0.9	-0.02	-0.33	-0.31	0.73	0.31	0.73
Southern hake	Chatham Rise	New Zealand[1]	1974	38	2	0.36	-0.03	-0.4	-0.38	0.2	0.05	0.2
Southern hake	Sub-Antarctic	New Zealand[1]	1974	40	2	0.39	0.01	0.29	0.28	0.1	0.42	0.1
Trevally	New Zealand	New Zealand[1]	1944	70	1	0.52	-0.17	0.76	0.93	#	#	#
Anchovy	South Africa	South Africa[1]	1984	31	2	0.39	0.12	0.03	-0.09	0.03	0.08	0.03
Cape horse mackerel	South Africa	South Africa[1]	1949	64	1	0.63	0.2	0.25	0.05	#	#	#
Deep water cape hake	South Africa	South Africa[1]	1920	95	2	0.17	0.13	0.32	0.19	0.79	0.55	0.79
Patagonian toothfish	South Africa	South Africa[1]	1960	55	2	0.46	-0.04	0.14	0.18	1.33	0.73	1.33
Sardine	South Africa	South Africa[1]	1986	29	2	0.25	0.14	0.82	0.68	0.44	0.39	0.44
Shallow water cape hake	South Africa	South Africa[1]	1920	95	2	0.7	0.2	1.01	0.81	0.9	0.79	0.9
South African abalone	South Africa	South Africa[1]	1951	64	2	0.18	-0.2	-0.19	0.01	0.11	0.06	0.11
Southern spiny lobster	South Africa	South Africa[1]	1973	41	2	0.29	0.15	-0.58	-0.73	1.31	1.3	1.31
Acadian redfish	US East Coast	USA[1]	1920	94	1	0.5	0.16	0.13	-0.03	#	#	#
Alaska plaice	US Alaska	USA[1]	1975	40	2	0.66	0.09	0.33	0.24	0.06	0.19	0.06
American plaice	Gulf of Maine	USA[1]	1980	34	2	0.29	0.46	0.45	-0.02	0.31	0.02	0.31

Arrowtooth flounder	Bering Sea	USA[1]	1976	39	2	1	0.06	0.44	0.38	0.05	0.01	0.05
Arrowtooth flounder	Gulf of Alaska	USA[1]	1961	54	1	0.98	0.03	0.15	0.12	#	#	#
Arrowtooth flounder	US West Coast	USA[1]	1920	95	1	0.78	0	0	0	#	#	#
Atka mackerel	US Alaska	USA[1]	1977	38	2	0.45	0.09	-0.55	-0.64	0.08	0.1	0.08
Atlantic butterfish	Gulf of Maine	USA[3]	1989	27	1	0.58	0.2	0.16	-0.04	#	#	#
Atlantic cod	Georges Bank	USA[1]	1978	33	1	0.23	0.54	0.47	-0.06	#	#	#
Atlantic cod	Gulf of Maine	USA[2]	2007	7	1	0.2	0.5	0.39	-0.11	#	#	#
Atlantic surfclam	Mid-Atlantic Coast	USA[3]	1982	29	2	0.42	0.18	-0.38	-0.57	0.02	0.37	0.02
Atlantic wolffish	Gulf of Maine	USA[3]	1968	48	2	0.15	0.31	0.34	0.03	0.24	0.01	0.24
Big skate	Gulf of Alaska	USA[3]	1990	29	1	0.91	-0.07	-0.03	0.04	#	#	#
Bigeye tuna	Atlantic	USA[3]	1950	59	1	0.49	0.06	0.11	0.05	#	#	#
Black sea bass	Mid-Atlantic Coast	USA[3]	1989	29	4	0.96	0.75	-0.12	-0.87	0.45	0.14	0.45
Blackspotted and Rougheye Rockfish	Gulf of Alaska	USA[3]	1977	39	1	0.72	-0.03	-0.13	-0.1	#	#	#
Blue king crab	Pribilof Islands	USA[3]	1976	43	3	0.01	0.53	0.19	-0.33	0.18	0.64	0.18
Blue king crab	Saint Matthew Island	USA[3]	1978	41	7	0.1	1.02	0.93	-0.09	0.54	0.26	0.54
Bluefish	Atlantic Coast	USA[3]	1985	33	3	0.49	-0.05	0.09	0.15	0.17	0.31	0.17
Bottomfish Multi-species Complex	Guam	USA[3]	1982	35	1	0.32	0.54	0.34	-0.2	#	#	#
Bottomfish Multi-species Complex	Main Hawaiian Islands	USA[3]	1949	64	1	0.51	0.08	0.2	0.12	#	#	#
Bottomfish Multi-species Complex	Northern Mariana Islands	USA[3]	2000	17	1	1	0.41	1.2	0.8	#	#	#
Brown shrimp	Gulf of Mexico	USA[3]	1984	33	3	0.2	-0.03	-0.06	-0.02	0.04	0.02	0.04
Cabezon	California	USA[3]	1920	89	1	0.48	-0.14	-0.09	0.05	#	#	#
Cabezon	Oregon	USA[3]	1970	49	1	0.53	0.09	0.29	0.2	#	#	#
California scorpionfish	Southern California	USA[3]	1920	97	2	0.55	0.19	-0.31	-0.5	0.36	0.03	0.36
Canary rockfish	Pacific Coast	USA[3]	1920	91	2	0.23	0.32	0.35	0.03	0.45	0.14	0.45
Cowcod	Southern California	USA[3]	1920	89	1	0.06	-0.09	0.08	0.16	#	#	#
Dover sole	US West Coast	USA[3]	1920	91	1	0.91	-0.14	0.08	0.21	0.2	0.07	0.2
Dover sole	Gulf of Alaska	USA[3]	1978	38	3	0.84	-0.24	-0.7	-0.45	#	#	#
Dusky rockfish	Gulf of Alaska	USA[3]	1977	41	4	0.83	-0.07	0.11	0.18	0.12	0.17	0.12
English sole	Pacific Coast	USA[3]	1920	87	1	0.99	0.03	-0.27	-0.3	#	#	#
Flathead sole	Bering Sea / Aleutian Islands	USA[3]	1964	54	10	0.67	-0.04	0.34	0.37	0.06	0.04	0.06
Flathead sole	Gulf of Alaska	USA[3]	1978	39	6	1	0.05	0.21	0.16	0.15	0.15	0.15

Gag	Gulf of Mexico	USA[3]	1963	49	1	0.38	0.39	0.74	0.35	#	#	#
Gag	Atlantic Coast	USA[3]	1962	50	1	0.85	-0.02	0.51	0.53	#	#	#
Golden king crab	Eastern Aleutian Islands	USA[3]	1986	31	1	1	0.06	-0.05	-0.1	#	#	#
Golden king crab	Western Aleutian Islands	USA[3]	1986	31	1	0.59	0.35	0.11	-0.24	#	#	#
Goosefish	Gulf of Maine	USA[3]	1980	31	2	0.68	0.48	0.72	0.24	0.55	0.17	0.55
Goosefish	Southern Georges Bank	USA[3]	1980	31	2	0.76	0.05	0.07	0.02	0.02	0.03	0.02
Greater amberjack	Gulf of Mexico	USA[3]	1950	65	1	0.11	0.48	0.37	-0.11	#	#	#
Greenland halibut	Bering Sea / Aleutian Islands	USA[3]	1945	73	12	0.16	0.04	0.13	0.09	0.28	0.29	0.28
Haddock	Eastern Georges Bank	USA[3]	1969	50	2	0.37	0.7	0.85	0.15	0.4	0.6	0.4
Haddock	Georges Bank	USA[3]	1964	52	4	1	0.65	0.44	-0.21	0.39	0.24	0.39
Haddock	Gulf of Maine	USA[3]	1977	39	4	1	0.59	-0.52	-1.11	0.24	0.04	0.24
Herring	Northwestern Atlantic Coast	USA[3]	1965	49	2	0.65	0.23	0.37	0.14	0.64	0.39	0.64
Kamchatka flounder	Bering Sea / Aleutian Islands	USA[3]	1991	27	2	0.84	0.21	0.2	-0.01	0.03	0.02	0.03
Kelp greenling	Oregon	USA[3]	1920	95	1	0.64	-0.59	-0.86	-0.27	#	#	#
Lingcod	Southern Pacific Coast	USA[3]	1920	99	1	0.41	0.02	0.04	0.01	#	#	#
Longnose skate	Pacific Coast	USA[3]	1920	99	1	0.57	0.12	-0.43	-0.56	#	#	#
Longspine thornyhead	Pacific Coast	USA[3]	1962	51	1	0.65	0.43	1.27	0.84	#	#	#
Mutton snapper	US Southeast and Gulf	USA[3]	1981	32	1	0.96	0.15	1.21	1.06	#	#	#
Northern rock sole	Bering Sea / Aleutian Islands	USA[3]	1976	42	11	0.78	-0.06	0.08	0.14	0.12	0.17	0.12
Northern rockfish	Bering Sea / Aleutian Islands	USA[3]	1977	39	4	0.98	-0.29	-0.32	-0.03	0.13	0.45	0.13
Northern rockfish	Gulf of Alaska	USA[3]	1961	57	6	0.56	-0.14	-0.43	-0.28	0.22	0.22	0.22
Other Flatfish Complex	Bering Sea / Aleutian Islands	USA[3]	2002	14	2	0.78	-0.05	-0.02	0.03	0.03	0.01	0.03
Other Skates Complex	Bering Sea / Aleutian Islands	USA[3]	2002	14	1	0.98	0	0.02	0.02	#	#	#
Pacific chub mackerel	Pacific Coast	USA[3]	2008	11	3	1	0.84	1.59	0.75	0.2	0.38	0.2
Pacific cod	Aleutian Islands	USA[3]	1991	27	3	0.48	-0.06	-0.05	0.01	0.04	0	0.04
Pacific cod	Bering Sea	USA[3]	1977	41	4	0.83	-0.08	0.32	0.4	0.25	0.34	0.25
Pacific cod	Gulf of Alaska	USA[3]	1977	41	11	0.15	0.45	0.47	0.01	0.28	0.47	0.28
Pacific hake	Pacific Coast	USA[3]	1966	53	11	0.56	-0.05	0.25	0.3	0.36	0.38	0.36
Pacific halibut	Pacific Coast / Alaska	USA[3]	1996	23	3	0.36	0.06	0	-0.06	0.02	0.01	0.02
Pacific ocean perch	Bering Sea / Aleutian Islands	USA[3]	1960	58	6	0.81	0.04	-0.6	-0.64	0.27	0.54	0.27
Pacific ocean perch	Gulf of Alaska	USA[3]	1961	57	7	0.75	0.08	-0.36	-0.44	0.11	0.43	0.11

Pacific ocean perch	Pacific Coast	USA[3]	1956	53	2	0.32	0.05	0.04	-0.01	0.03	0.01	0.03
Pacific sardine	US West Coast	USA[3]	1994	22	1	0.02	0.31	0.32	0	0.8	0.28	0.8
Pacific sardine	Northern Subpopulation	USA[3]	2006	13	3	0.08	-0.94	-0.29	0.65	#	#	#
Petrale sole	Pacific Coast	USA[3]	1920	99	5	0.42	0.08	-0.06	-0.13	0.43	0.14	0.43
Pink shrimp	Gulf of Mexico	USA[3]	1984	33	3	0.23	0.04	-0.23	-0.27	0.1	0.1	0.1
Pollock	Gulf of Maine	USA[3]	1970	46	3	0.49	-0.12	-0.24	-0.12	0.13	0.17	0.13
Red king crab	Bristol Bay	USA[3]	1976	42	9	0.19	1.15	0.11	-1.04	0.44	0.3	0.44
Red king crab	Norton Sound	USA[3]	1976	41	5	0.26	0.22	-0.08	-0.3	0.09	0.21	0.09
Red porgy	Southern Atlantic Coast	USA[3]	1972	45	1	0.16	-0.08	0.25	0.32	#	#	#
Rex sole	Gulf of Alaska	USA[3]	1982	29	1	1	0.08	0.01	-0.07	#	#	#
Rougheye rockfish	Bering Sea	USA[3]	1977	37	1	1	0.39	0.38	-0.01	#	#	#
Rougheye rockfish	Gulf of Alaska	USA[3]	1977	32	1	0.82	0	0.05	0.06	#	#	#
Sablefish	Eastern Bering Sea	USA[3]	1960	58	13	0.32	0.15	0.17	0.03	0.19	0.16	0.19
Sablefish	Pacific Coast	USA[3]	1920	99	4	0.31	0.09	0.15	0.05	0.14	0.27	0.14
Sculpin Complex	Gulf of Alaska	USA[3]	1984	33	1	0.79	0.15	-0.02	-0.17	#	#	#
Scup	Atlantic Coast	USA[3]	1984	34	6	0.79	0.06	-0.15	-0.21	0.12	0.13	0.12
Sea scallop	Northwestern Atlantic Coast	USA[3]	1976	41	3	1	0.93	0.12	-0.8	0.11	0.14	0.11
Shortraker rockfish	Bering Sea / Aleutian Islands	USA[3]	2002	16	5	1	-0.11	-0.16	-0.05	0.14	0.04	0.14
Shortspine thornyhead	Gulf of Alaska	USA[3]	1984	33	1	0.87	0.03	0.01	-0.02	#	#	#
Shortspine thornyhead	Pacific Coast	USA[3]	1920	93	1	0.71	-0.15	-0.57	-0.42	#	#	#
Snow crab	Bering Sea	USA[3]	1982	34	7	0.39	0.05	0.66	0.62	0.52	0.62	0.52
Snowy grouper	US Southeast and Gulf	USA[3]	1974	38	1	0.25	-0.3	0.63	0.93	#	#	#
Southern Tanner crab	Bering Sea	USA[3]	1976	41	4	0.37	-0.32	0.03	0.35	0.31	0.35	0.31
Spanish mackerel	US Southeast and Gulf	USA[3]	1950	61	1	0.51	-0.41	0.24	0.65	#	#	#
Spiny dogfish	Atlantic Coast	USA[3]	1991	27	1	0.46	0.66	0.8	0.14	#	#	#
Striped bass	US East Coast	USA[3]	1982	30	1	0.76	-0.16	-0.53	-0.37	#	#	#
Summer flounder	Mid-Atlantic Coast	USA[3]	1982	35	7	0.64	0.08	-0.19	-0.27	0.11	0.09	0.11
Swordfish	North Atlantic	USA[3]	1950	61	2	0.6	0.01	-0.13	-0.14	0.09	0.13	0.09
Tanner crab	US Alaska	USA[3]	1965	50	2	0.17	0.19	0.04	-0.15	0.3	0.36	0.3
Tilefish	Mid-Atlantic Coast	USA[3]	1971	45	1	0.3	-0.42	-0.47	-0.06	#	#	#
Walleye pollock	Aleutian Islands	USA[3]	1978	40	11	0.28	0.11	0.13	0.02	0.14	0.49	0.14

Walleye pollock	Bogoslof	USA[3]	1990	26	2	0.35	-0.37	-0.36	0.01	0.59	0.02	0.59
Walleye pollock	Eastern Bering Sea	USA[3]	1964	53	12	0.97	-0.07	-0.05	0.03	0.15	0.02	0.15
Walleye pollock	West Yakutat Gulf of Alaska	USA[3]	1977	41	13	0.65	-0.43	-0.21	0.22	0.13	0.2	0.13
White hake	Gulf of Maine	USA[3]	1963	53	3	0.56	0.18	0.31	0.13	0.14	0.3	0.14
White shrimp	Gulf of Mexico	USA[3]	1984	33	2	0.39	-0.17	-0.24	-0.07	0.03	0.03	0.03
Widow rockfish	Pacific Coast	USA[3]	1920	99	4	0.86	-0.26	-0.33	-0.07	0.4	0.37	0.4
Winter flounder	Georges Bank	USA[3]	1982	34	4	0.23	0.09	0.07	-0.02	0.55	0.03	0.55
Winter flounder	Gulf of Maine	USA[3]	2009	7	1	0.49	0	0.37	0.37	#	#	#
Winter flounder	Southern New England	USA[3]	1981	35	4	0.2	0.03	-0.21	-0.23	0.41	0.2	0.41
Witch flounder	Northwestern Atlantic Coast	USA[3]	1982	32	3	0.12	0.77	0.85	0.08	0.68	0.13	0.68
Yelloweye rockfish	Pacific Coast	USA[3]	1925	82	2	0.16	0.24	0.39	0.15	0.28	0.1	0.28
Yellowfin sole	Bering Sea / Aleutian Islands	USA[3]	1954	64	12	0.74	-0.17	-0.42	-0.25	0.19	0.14	0.19
Yellowtail flounder	Cape Cod / Gulf of Maine	USA[3]	1985	31	3	0.48	0.2	0.38	0.18	0.53	0.21	0.53
Yellowtail flounder	Georges Bank	USA[3]	1973	38	2	0.21	0.94	0.94	0	0.37	0	0.37
Yellowtail flounder	Southern New England	USA[3]	1973	43	4	0.01	-0.11	0.04	0.15	0.97	0.14	0.97

Table S1.
Historical retrospective analyses for stocks investigated (i.e. Species × Region combinations) and different national and trans-national assessment groups. Results show initial year of stock data (year), number of years modeled from initial year (years), the number of assessment comparisons for each stock (N = number of stock assessments less most recent assessment), most current biomass depletion estimate as provided in most recent assessment (B/Bmax), bias (□) metrics as natural logarithms for B/Bmax, spawning stock biomass (B), and maximum biomass (Bmax), and standard deviation (SD) in bias (□) metrics for stock assessments conducted in different years within a stock. □□statistics were averaged across assessments for each stock. # indicates no SD data as only one comparison with most recent assessment (MRA). Positive bias indicates over-estimation at the time of stock assessment relative to MRA. ICES: Multinational European stocks assessed through the International Council for the Exploration of the Sea. Data source is shown by superscript with National group: 1RAM Legacy version 1.0, downloaded 15 Aug 2011 (1) ; 2RAM Legacy version 4.46 (downloaded on 2 July 2020); 3SMART compilation of data for USA fisheries (2); 4Modeled biomass trends for 16 Australian South East Scalefish and Shark Fishery stocks (3).

Model	Standard Error	WAIC
$\Delta B/B_{max}$ ~ (value + assessment age) * depletion + duration + SST trend + mean SST + clupeoid + (1 | stock)	59.3	420.2
$\Delta B/B_{max}$ ~ (mean SST + value + assessment age) * depletion + duration + clupeoid + SST trend + (1 | stock)	59.1	420.6
$\Delta B/B_{max}$ ~ (duration + mean SST + SST trend + value + assessment age) * depletion + clupeoid + (1 | stock)	59.4	421.2
$\Delta B/B_{max}$ ~ (mean SST + SST trend + value + assessment age) * depletion + duration + clupeoid + (1 | stock)	59.2	423.3
$\Delta B/B_{max}$ ~ assessment age * depletion + duration + SST trend + mean SST + value + clupeoid + (1 | stock)	60.0	423.7
$\Delta B/B_{max}$ ~ assessment age + depletion + duration + SST trend + mean SST + value + clupeoid + (1 | stock)	62.3	451.1

Table S2.
Results of generalized linear mixed models fitted for $\Delta B/B_{max}$ assessing model fit using different interaction terms. Models are given in R syntax, where '*' indicates inclusion of an interaction and all main effects, (1|stock) indicates a random group effect.

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