Supplementary materials

In the supplementary materials included in this document, we provide details of the operating model used for simulation testing along with some auxiliary results. Settings and model parameters for the bottomfish life history pattern are listed in Supplementary Table 1. The bottomfish life history scenario used the exact same fishery system and life history parameter values as Li et al. (2021). This scenario represented a bottomfish species with moderate longevity and annual productivity, which is a common assessment situation (Suppl. Table 1).

The operating model included an age-structured population dynamics model with life history characteristics and parameters for growth, natural mortality, maturity at age, and the spawner-recruit relationship. Fishing and natural mortality occurred continuously in each annual time step, and the expected natural mortality rate was a constant across age classes. Growth in length at age was modeled as a von Bertalanffy curve, and weight at length was modeled with an allometric curve. Maturity probability at age was based on a logistic ogive. Stock-recruitment dynamics were based on a Beverton–Holt curve with a multiplicative lognormal process error. The fishery and survey fleets were modeled by using logistic selectivity at age, with the exception of a dome-shaped double-logistic curve used in one of the test cases. The fishery observation consisted of catch biomass by time step with lognormal error along with catch-at-age data with multinomial errors. The research survey observations consisted of a survey index by time step observed with lognormal errors along with survey catch-at-age data with multinomial errors.

The equations for the operating model used to generate age-structured population dynamics and fishery and simulated observational data are provided in Supplementary Table 2. This table includes the sub-models for life history parameters, the stock-recruitment relationship, initial conditions, population dynamics, fishing fleet dynamics, research survey dynamics, fishing mortality, and simulated observational data.

Auxiliary simulation testing results for estimation accuracies of relative spawning biomass and relative fishing mortality are reported in Supplementary Table 3. The calculated median absolute relative error (MARE) and median relative error (MRE) values for the r4MAS package are listed along with the corresponding range of estimation performance metrics reported by Li et al. (2021, table 6) where available.

The relative variabilities of MARE values expressed as percentages of the MARE are listed in Supplementary Table 4. The ratio of the median absolute deviation to the MARE provides a measure of the relative accuracy of estimates of relative spawning biomass, the ratio of spawning biomass to the spawning biomass required to produce maximum sustainable yield (MSY); relative fishing mortality, the ratio of fishing mortality to the fishing mortality required to produce MSY; spawning biomass; recruitment; and fishing mortality for each test case.

Estimation accuracies for the auxiliary quantities of interest of spawning biomass, recruitment, and fishing mortality are shown in Supplementary Figures 1–3.

Supplementary Table 1. Descriptions and settings for operating model parameters for the bottomfish life history scenario. The parameters include index variables, structural parameters, state variables, derived variables, and stochastic variation used to generate simulated data.

Model parameter	Description	Case-1	Estimated?
Index variables			
t	Time period (year)	$\{1,2,...,Y\}, Y=30$	
a	Ages (year)	$\{1,2,...,A\}, A=12+$	
Structural parameters			
L_{inf}	Asymptotic mean length (mm)	800	
k	Brody growth coefficient (year^{-1})	0.18	
t_0	Age at zero mean length (year)	−1.36	
θ_1	Length–weight intercept	2.500×10^{-8}	
θ_2	Length–weight exponent	3	
θ_3	Slope of maturity ogive	3	
a_{50}	Age at 50% maturity (year)	2.25	
M_a	Natural mortality rate at age (year^{-1})	0.20	
r	Proportion of females	0.50	
R_0	Unfished recruitment (age-1 fish per year)	1.0×10^6	Yes
h	Stock-recruitment steepness	0.75	
x_1	Fishery selectivity slope	1	Yes
x_2	Fishery selectivity age at 50% selection	2	Yes
x_3	Survey selectivity slope	2	Yes
x_4	Survey selectivity age at 50% selection	1.5	Yes

Supplementary Table 1. Continued.

Model Parameter	**Description**	**Case-1**	**Estimated?**
β_1	Slope of double-logistic fishery selectivity	0.70	Yes
β_2	Inflection point of double-logistic fishery selectivity	11	Yes
β_3	Slope of double-logistic fishery selectivity	0.37	Yes
β_4	Inflection point of double-logistic fishery selectivity	12	Yes
f_t	Time series of fully selected *F* at time *t*	$f_t = 0.013103t - 0.003103$	
φ_F	Fishery sample size for age composition	200	
φ_I	Survey sample size for age composition	200	
State variables			
R_t	Expected recruitment at time *t*		
SB_t	Spawning biomass at time *t*		
$N_{a,t}$	Numbers at age *a* at time *t*		
N_t	Population numbers at time *t*		
B_t	Population biomass at time *t* (metric ton)		
$C_{a,t}$	Catch numbers at age *a* at time *t*		
L_t	Landings at time *t* (metric ton)		
L'_t	Observed landings at time *t* (metric ton)		
$I_{a,t}$	Survey numbers at age *a* at time *t*		
I_t	Survey numbers at time *t*		
I'_t	Observed survey numbers at time *t*		
$P_{C_a,t}$	Proportion at age *a* at time *t* in the fishery		
$P'_{C_a,t}$	Observed proportion at age *a* at time *t* in the fishery		
$P_{I_a,t}$	Proportion at age *a* at time *t* in the survey		

Supplementary Table 1. Continued.

Model Parameter	Description	Case-1	Estimated?
$P'_{I_a,t}$	Observed proportion at age *a* at time *t* in the survey		
Derived variables			
L_a	Mean length at age *a*		
W_a	Mean weight at age *a*		
P_a	Proportion mature at age *a*		
ϕ_0	Unfished spawning biomass per recruit (metric ton)		
$Z_{a,t}$	Total mortality at age *a* at time *t*		
F_t	Fully selected *F* at time *t*		
$S_{F,a}$	Fishery selectivity at age *a*		
$S_{I,a}$	Survey selectivity at age *a*		
Φ_a	Survivors per recruit at age *a*		
ϕ_F	Spawning biomass per recruit at fishing mortality *F*		
R_{eq}	Equilibrium recruitment		
q	Catchability coefficient for survey	3.32×10^{-7}	Yes
Process errors			
σ_R	Standard deviation of log-scale recruitment	0.20	
$R_{\Delta t}$	Recruitment deviation at time *t*	$R_{\Delta t} \sim N\left(0, \sigma_R^2\right)$	Yes
σ_F	Standard deviation of log-scale *F*	0.20	
$F_{\Delta t}$	Fully selected *F* deviation at time *t*	$F_{\Delta t} \sim N\left(0, \sigma_F^2\right)$	Yes

Supplementary Table 1. Continued.

Model Parameter	Description	Case-1	Estimated?
Observation errors			
CV_L	Coefficient of variation of landings	0.05	
$\varepsilon_{1,t}$	Landings deviation at time *t*	$\varepsilon_{1,t} \sim N\left(0, \log\left(1 + CV_L^2\right)\right)$	
CV_I	Coefficient of variation of survey index	0.20	
$\varepsilon_{2,t}$	Survey numbers deviation at time *t*	$\varepsilon_{2,t} \sim N\left(0, \log\left(1 + CV_I^2\right)\right)$	

Supplementary Table 2. Description of operating model equations used to generate age-structured population dynamics, relative abundance indices, and age compositions.

Life history parameters

1.1. Length at age *a*

$$L_a = L_{\text{inf}}\left(1-\exp\left(-k\left(a-t_0\right)\right)\right)$$

1.2. Weight at length at age *a*

$$W_a = \theta_1 \cdot L_a^{\theta_2}$$

1.3. Maturity probability at age *a*

$$P_a = \frac{1}{1+\exp\left(-\theta_3\left(a-a_{50}\right)\right)}$$

Stock-recruitment relationship

2.1. Unfished spawning biomass per recruit

$$\phi_0 = \sum_{a=1}^{A} \phi'_a \, r_a P_a W_a \quad \text{where}$$

$$\phi'_a = \begin{cases} 1 & a=1 \\ \phi'_{a-1}\, e^{-M_{a-1}} & 1<a<A \\ \dfrac{\phi'_{A-1}\, e^{-M_{A-1}}}{1-e^{-M_A}} & a=A \end{cases}$$

2.2. Expected recruitment at time *t*+1

$$R_{t+1} = \frac{0.8R_0 \cdot h \cdot SSB_t}{0.2R_0 \cdot \phi_0 \cdot \left(1-h\right)+SSB_t \cdot \left(h-0.2\right)}$$

Initial conditions

3.1. Total mortality at age *a*

$$Z_{a,1} = F_1 \cdot S_{F,a} + M_a$$

3.2. Survivors per recruit at age *a*

$$\Phi_a = \begin{cases} 1 & a=1 \\ \Phi_{a-1} \cdot \exp\left(-Z_{a-1,1}\right) & 1<a<A \\ \dfrac{\Phi_{A-1} \cdot \exp\left(-Z_{A-1,1}\right)}{1-\exp\left(-Z_{A,1}\right)} & a=A \end{cases}$$

3.3. Spawning biomass per recruit given F

$$\phi_F = \sum_{a=1}^{A} r_a P_a W_a \cdot \Phi_a$$

3.4. Equilibrium recruitment given F

$$R_{eq} = \frac{R_0\left(4h \cdot \phi_F - (1-h)\phi_0\right)}{(5h-1)\phi_F}$$

3.5. Initial numbers at age a

$$N_{a,1} = R_{eq} \cdot \Phi_a$$

3.6. Initial spawning biomass

$$SSB_1 = \sum_{a=1}^{A} r_a P_a W_a \cdot N_{a,1}$$

Population dynamics

4.1. Recruitment at time t

$$N_{1,t} = R_t \cdot \exp\left(R_{\Delta t}\right)$$

4.2. Total mortality at age a and time t

$$Z_{a,t} = F_t S_{F,a} + M_a$$

4.3. Numbers at age (a<A) at time t+1

$$N_{a,t+1} = N_{a-1,t} \cdot \exp\left(-Z_{a-1,t}\right)$$

4.4. Numbers in the plus-group age A at time t+1

$$N_{A,t+1} = N_{A-1,t} \cdot \exp\left(-Z_{A-1,t}\right) + N_{A,t} \cdot \exp\left(-Z_{A,t}\right)$$

4.5. Spawning biomass at time t

$$SSB_t = r\sum_{a=1}^{A} P_a W_a \cdot N_{a,t}$$

4.6. Total numbers at time t

$$N_t = \sum_{a=1}^{A} N_{a,t}$$

4.7. Total biomass at time t

$$B_t = \sum_{a=1}^{A} N_{a,t} W_a$$

Fleet dynamics

5.1. Fishery logistic selectivity at age a

$$S_{F,a} = \frac{1}{1+\exp\left(-x_1\left(a-x_2\right)\right)}$$

5.2. Catch numbers at age a and time t

$$C_{a,t} = \frac{F_t S_{F,a}}{Z_{a,t}} N_{a,t}\left(1-\exp\left(-Z_{a,t}\right)\right)$$

5.3. Total landed weight at time t

$$L_t = \sum_{a=1}^{A} C_{a,t} W_a$$

5.4. Fishery double-logistic selectivity at age a

$$S'_{F,a} = \frac{1}{1+\exp\left(-x_1\left(a-x_2\right)\right)} \cdot \frac{1}{1-\exp\left(-\beta_1\left(a-\beta_2\right)\right)} \quad \text{and}$$

$$S_{F,a} = \frac{S'_{F,a}}{\max\limits_a\left(S'_{F,a}\right)}$$

Survey dynamics

6.1. Survey logistic selectivity at age a

$$S_{I,a} = \frac{1}{1+\exp\left(-x_3\left(a-x_4\right)\right)}$$

6.2. Survey catchability

$$q = \frac{1}{T^{-1}\sum_{t=1}^{T}\sum_{a=1}^{A} N_{a,t} S_{I,a}}$$

6.3. Survey numbers at age a at the start of the year

$$I_{a,t} = N_{a,t} S_{I,a}$$

6.4. Survey index at time t

$$I_t = q\sum_{a=1}^{A} I_{a,t}$$

6.5. Survey double-logistic selectivity at age *a*

$$S'_{I,a} = \frac{1}{1+\exp\left(-x_3\left(a-x_4\right)\right)} \cdot \frac{1}{1-\exp\left(-\beta_3\left(a-\beta_4\right)\right)} \quad \text{and}$$

$$S_{I,a} = \frac{S'_{I,a}}{\max_a\left(S'_{I,a}\right)}$$

Fishing mortality time series

7.1. Predicted fishing mortality at time *t*

$$F_t = f \cdot \exp\left(F_{\Delta t}\right)$$

Observed data with simulated error

8.1. Observed landings at time *t* with lognormal distribution

$$L_t^* \sim LN\left(L_t - 0.5\sigma_L^2,\ \sigma_L^2\right)$$

8.2. Fishery catch proportion at age *a* and time *t*

$$P_{C_{a,t}} = \frac{C_{a,t}}{\sum_{a=1}^{A} C_{a,t}}$$

8.3. Observed fishery age composition at time *t* with multinomial distribution

$$\underline{C^*_{F,t}} \sim Multinomial\left(\varphi_F, \underline{P_{C_t}}\right)$$

8.4. Observed survey index at time *t* with lognormal distribution

$$I_t^* \sim LN\left(I_t - 0.5\sigma_I^2,\ \sigma_I^2\right)$$

8.5. Survey catch proportion at age *a* and time *t*

$$P_{I_{a,t}} = \frac{I_{a,t}}{\sum_{a=1}^{A} I_{a,t}}$$

8.6. Observed survey age composition at time *t* with multinomial distribution

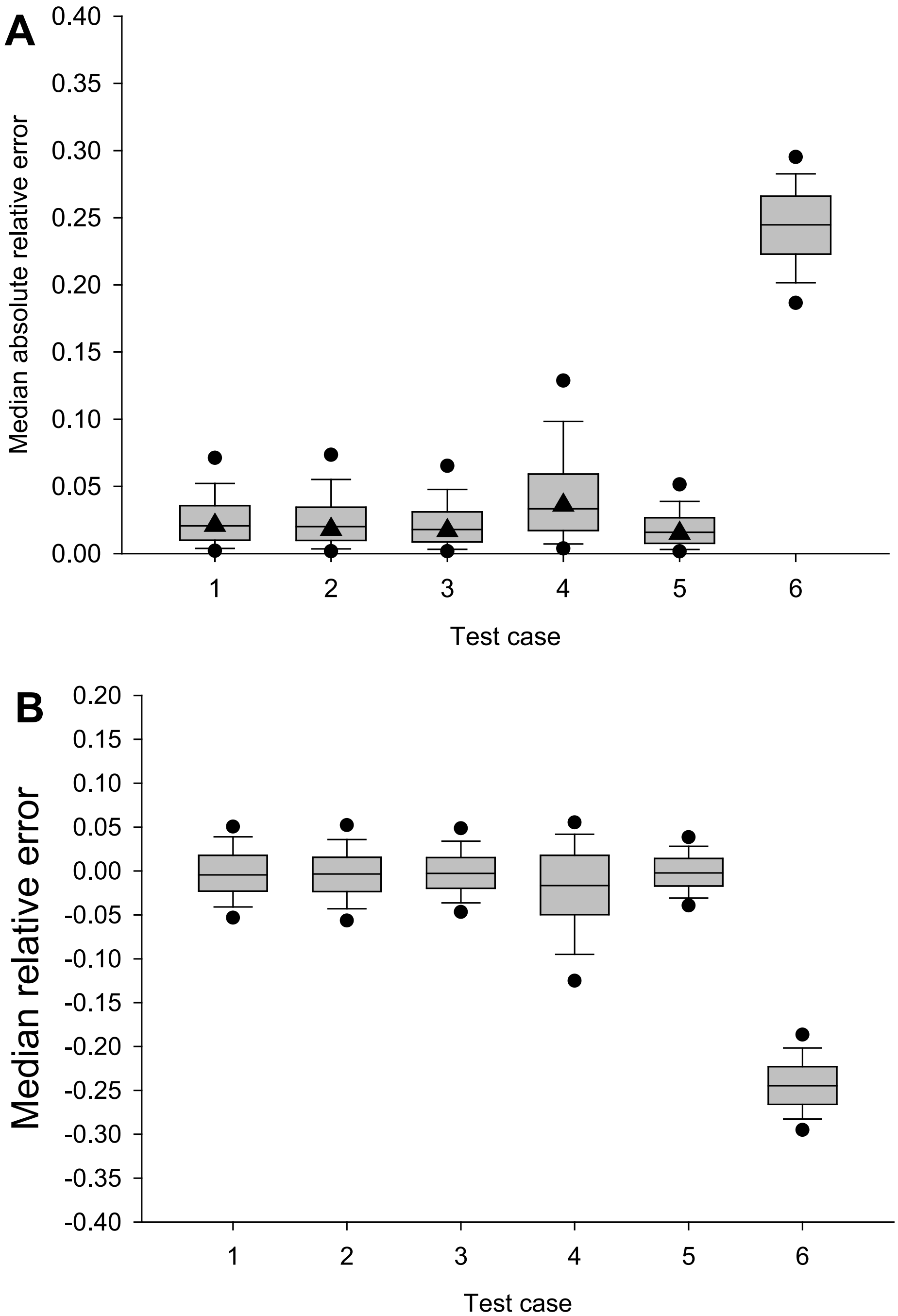
$$\underline{C^*_{I,t}} \sim Multinomial\left(\varphi_I, \underline{P_{I_t}}\right)$$

Supplementary Table 3. Means of the median absolute relative error (MARE) and median relative error (MRE), expressed as percentages, for estimation of relative spawning biomass (*SB/SB*MSY) and relative fishing mortality (*F/F*MSY) across simulations and years by test case. The range of comparable MARE values from the models tested in Li et al. (2021) (test cases 1–5) are given in italic type below the MARE values from this study.

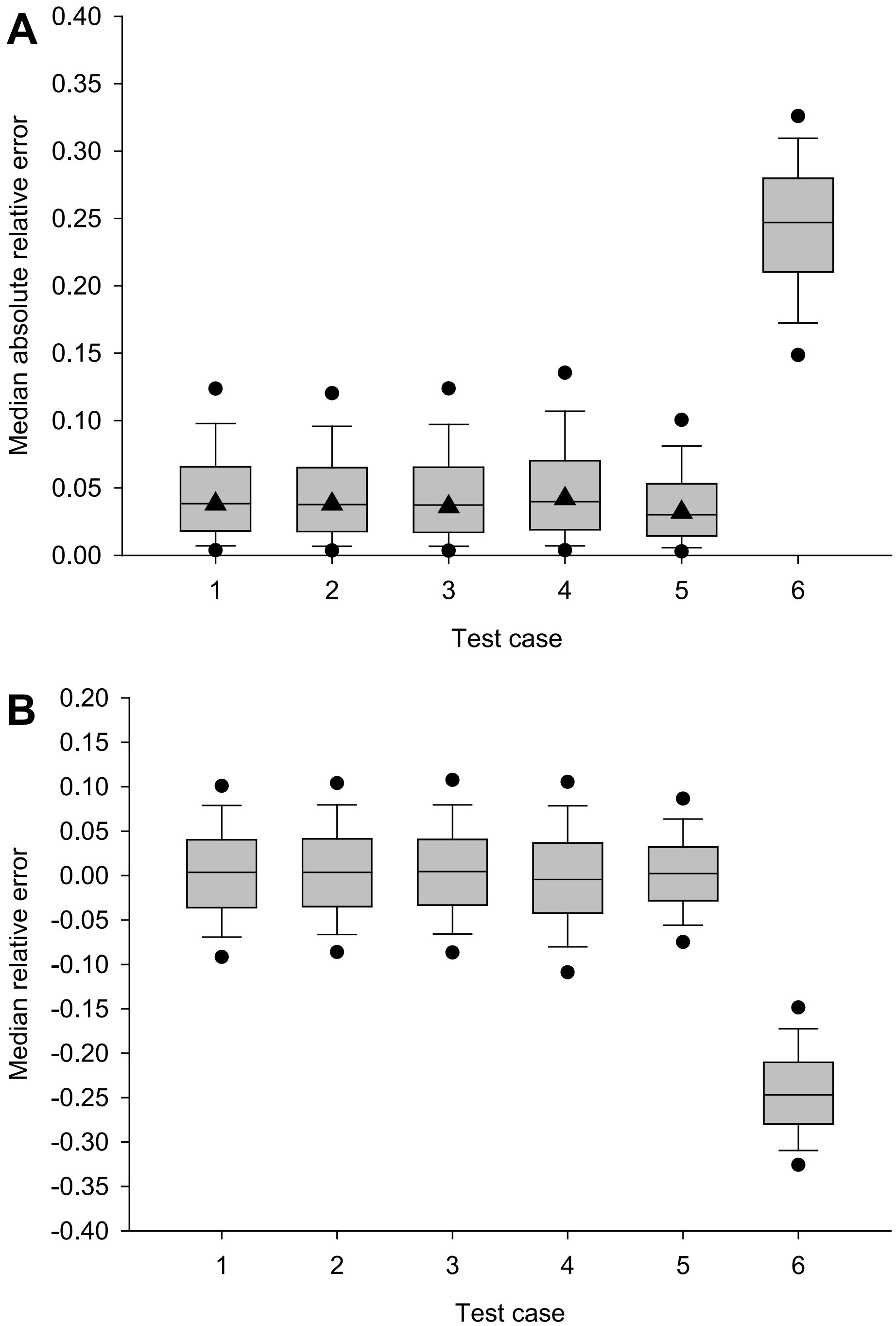
Test case	MARE of ***SB/SB*MSY**	MARE of ***F/F*MSY**	MRE of ***SB/SB*MSY**	MRE of ***F/F*MSY**
Case 1	4.2 *3.7–4.3*	2.5 *2.0–2.1*	−0.5	0.0
Case 2	4.1 *3.7–3.8*	2.4 *1.9–1.9*	−1.1	0.2
Case 3	5.1 4.1–4.5	2.3 *2.0–2.3*	−0.9	−0.1
Case 4	4.6 *4.0–6.0*	3.3 *3.3–5.0*	−2.4	1.4
Case 5	3.8 *3.4–3.5*	1.8 *1.7–1.8*	−0.5	−0.1
Case 6	4.2	5.3	−0.4	−0.8

Supplementary Table 4. The median absolute deviation (MAD) expressed as a percentage of the median absolute relative error (MARE), or the ratio of MAD to MARE, providing a measure of the relative variability for estimates of relative spawning biomass (SB/SB_{MSY}), relative fishing mortality (F/F_{MSY}), spawning biomass (*SB*), recruitment (*R*), and fishing mortality (*F*) for each test case.

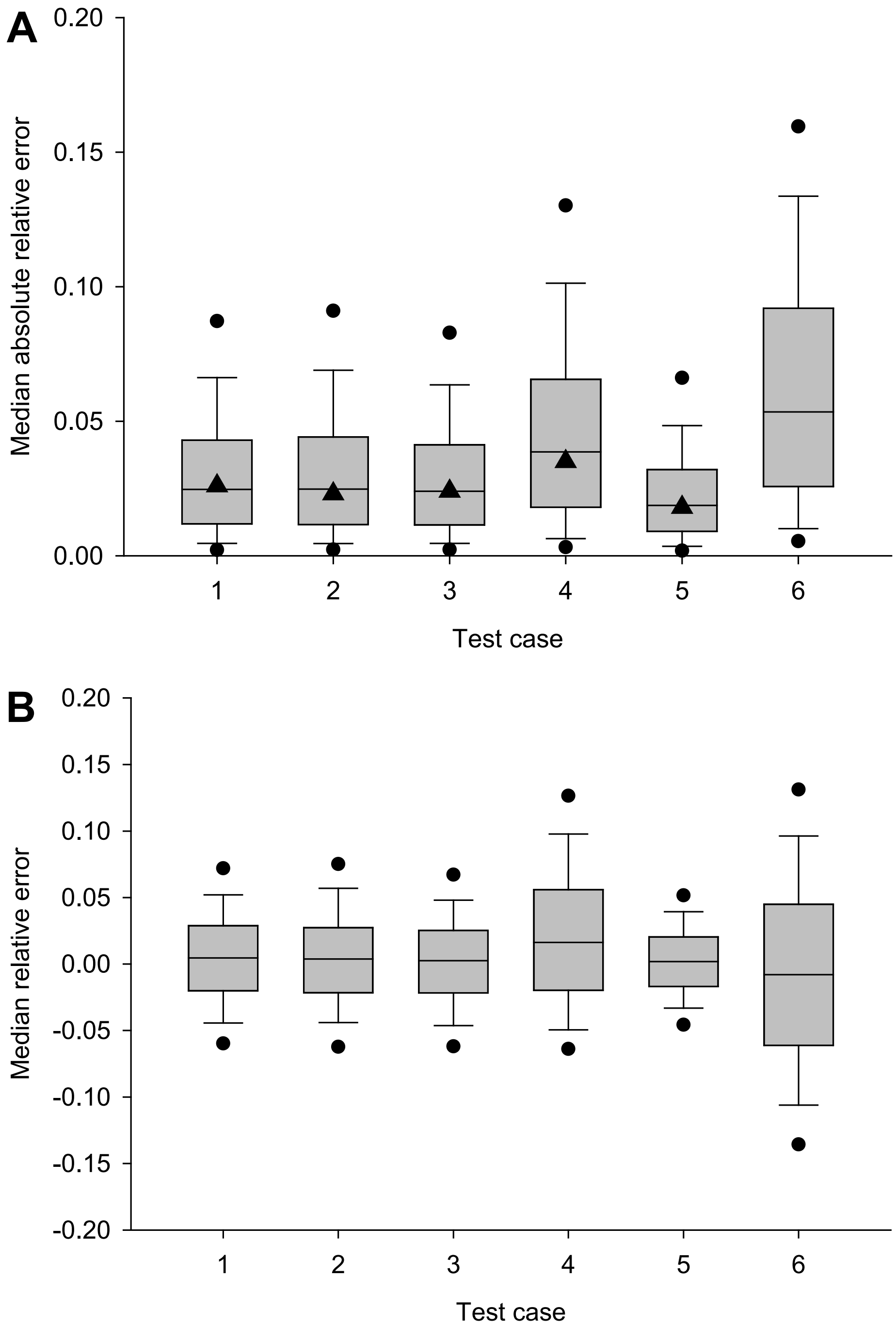
Simulation	Relative *SB*	Relative *F*	*SB*	*R*	*F*
Test case 1	9%	13%	13%	10%	13%
Test case 2	8%	17%	23%	12%	16%
Test case 3	6%	19%	16%	16%	16%
Test case 4	8%	17%	26%	9%	21%
Test case 5	7%	17%	14%	12%	11%
Test case 6	9%	17%	1%	4%	18%



Supplementary Figure 1. Box plots of (**A**) median absolute relative estimation errors (MAREs) and (**B**) median relative errors for estimation of spawning biomass with 6 test cases in the Metapopulation Assessment System under the scenario for a simulated population based on life history traits. The black circles indicate the 5th and 95th percentiles. The triangles in panel A indicate the minimum MARE values reported for tests 1–5 reported by Li et al. (2021). For details about the test cases, see the "Simulation testing" section in the main article.



Supplementary Figure 2. Box plots of (**A**) median absolute relative errors (MAREs) and (**B**) median relative errors for estimation of recruitment with 6 test cases in the Metapopulation Assessment System under the scenario for a simulated population based on life history traits. The black circles indicate the 5th and 95th percentiles The triangles in panel A indicate the minimum MARE values reported for tests 1–5 reported by Li et al. (2021). For details about the test cases, see the “Simulation testing” section in the main article.



Supplementary Figure 3. Box plots of (**A**) median absolute relative errors (MAREs) and (**B**) median relative errors for estimation of fishing mortality with 6 test cases in the Metapopulation Assessment System under the scenario for a simulated population based on life history traits. The black circles indicate the 5th and 95th percentiles The triangles in panel A indicate the minimum MARE values reported for tests 1–5 reported by Li et al. (2021). For details about the test cases, see the "Simulation testing" section in the main article.