A REVIEW AND EVALUATION OF NATURAL MORTALITY FOR THE ASSESSMENT AND MANAGEMENT OF YELLOWFIN TUNA IN THE EASTERN PACIFIC OCEAN

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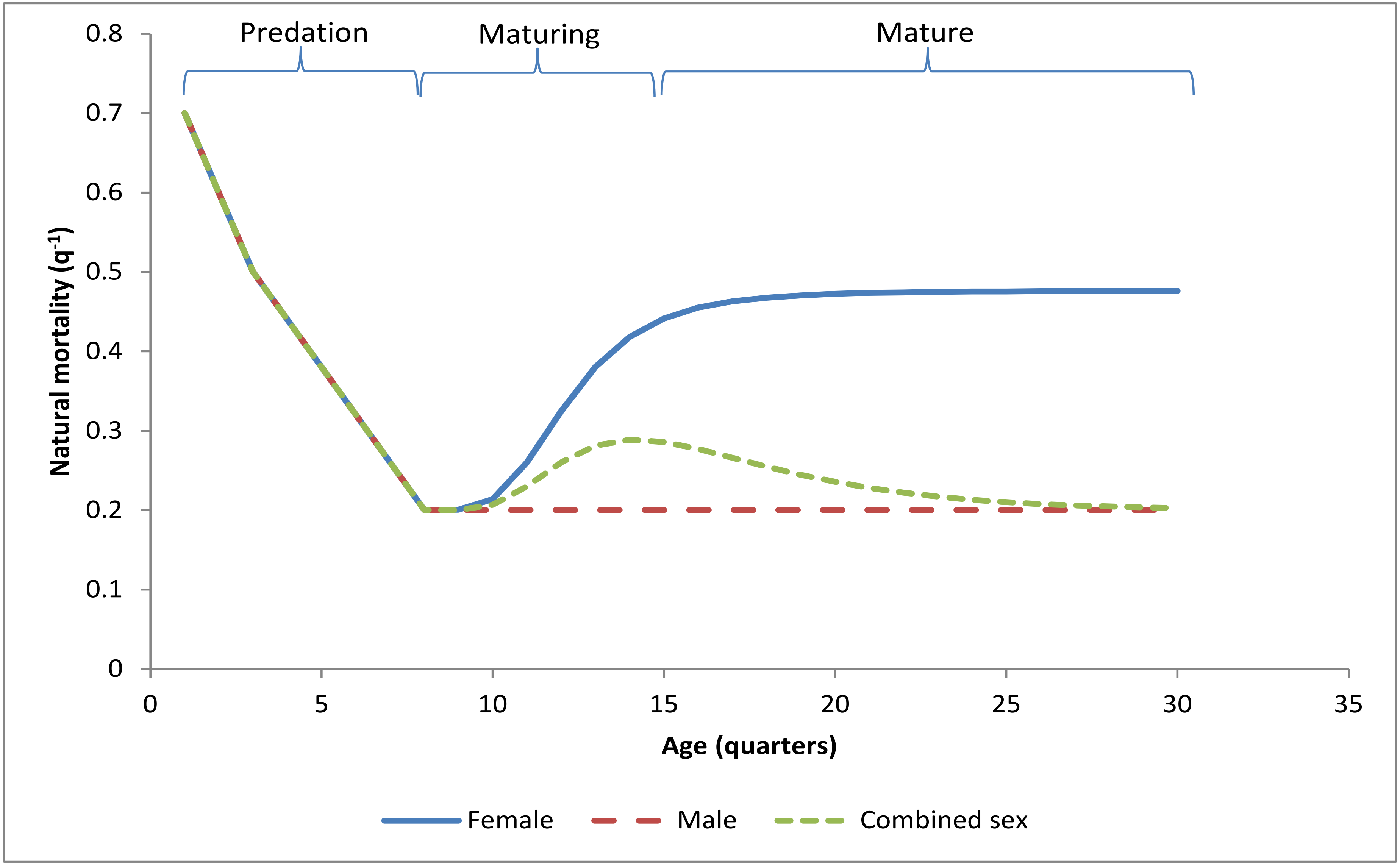
Outline

- YFT history
- Methods to estimate M
  - Maximum age
  - Life history
  - Tagging studies
  - Estimating M inside the stock assessment model
  - Age, sex, and time specific M
  - M for other stocks and species
- Simulation analysis
- Actual estimates
- Management consequences
- Summary and recommendations

YFT history

- Cohort analysis (Pat Tomlinson)
  - M was assumed to increase for females after they reach the age of 30 months (7-8 quarters) while the male M stayed at the base value of 0.8 y^{-1}
  - Estimated to fit sex ratio data
- ASCALA/SS
  - M at age zero is set to 0.7
  - Linear decline to age 7 quarters (nearly)
  - Mature females have higher M
  - Use proportion mature to adjust female M at age
  - Fit to sex ratio data
  - Adjusted to be similar to WCPO estimates from tagging data (Hampton 2000)



Predation
Maturing
Mature
Natural mortality (q-1)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
Age (quarters)
Female
Male
Combined sex

Sex ratio

- Ratio of male to female yellowfin in the catch favoring males as the size of the fish in the catch increases
  - 1) Large females are less vulnerable to fishing than large males
    - i.e. large females do not occur in the main fishing areas or are segregated from males vertically in the water column
    - sex ratio changes with age occur in both the longline and purse-seine fisheries
  - 2) Females grow more slowly than males;
    - There is a lack of Information on the size at age of large yellowfin
    - Wild (1986) reporting gender differences in growth rates (females may be smaller than males after around age 3)
    - No evidence of the accumulation of females (i.e. sex ratio favoring females) at intermediate sizes.
    - Energetic cost of reproduction could reduce both growth and survival simultaneously.
  - 3) Large females die at a more rapid rate than do large males (perhaps because the physiological costs of reproduction are higher for females).

Maximum age

- The lower the mortality rate, the longer individuals live.
- Rule of thumb ($M=3/a_{max}$)
- Criticized for a number of reasons
  - estimate of total mortality.
  - dependent on the sample size.
  - Assumes a single value of M for all ages.
  - Based on the empirical relationship of Hoenig (1983), Hewitt and Hoenig (2005) suggest using $4.22/a_{max}$.
  - Hoenig's (1983) relationship has large prediction error.
- Maximum age is difficult to determine for yellowfin tuna.
- The longest time at liberty for YFT in the EPO is 8 years for a yellowfin tuna released at age 1 for an estimated age of 9 years.
- The EPO yellowfin tuna stock has been exploited for over 50 years.
- The gender of these tagged fish was not recorded, so gender specific a_{max} cannot be determined.

Life history

- Theoretical
  - Jensen's (1996) growth rate parameter (K) and the age at maturity.
- Empirical
  - Pauly's (1980) growth rate, asymptotic size, and water temperature.
  - Gunderson's (1997) gonad index.
- Predictions are imprecise and uncertainty in the life history parameters.
- EPO yellowfin tuna growth does not follow the von Bertalanffy curve.
- Estimates of the asymptotic length are uncertain for EPO yellowfin.

Life history

Reference	Equation	Quantity	M (q^{-1}) estimate
Rule of thumb	$3/a_{max}$	$a_{max} = 9$	0.0825
Hoenig (1983)	$Exp(1.46-1.01ln[a_{max}])$	$a_{max} = 9$	0.1175
Jensen (1996) K vonB	1.60K	K = 0.09	0.035
Jensen (1996) K Richards	1.60K	K = 0.69	0.275
Jensen (1996) a_{mat}	$1.65/a_{mat}$	$a_{mat} = 1.3$ male $a_{mat} = 2.0$ female	0.3175 male 0.2075 female
Pauly (1980) K von B	$Exp(-0.0152-0.279ln[L_{inf}]+0.6543ln[K]+0.4634ln[T])$	$L_{inf} = 484.55$, K = 0.09,T = 25	0.04
Pauly (1980) K Richards	$Exp(-0.0152-0.279ln[L_{inf}]+0.6543ln[K]+0.4634ln[T])$	$L_{inf} = 185.01$, K = 0.69,T = 25	0.2
Gunderson (1997)	1.79GSI	GSI = NA	NA

Tagging studies

- Hampton (2000) applied tag-attrition analysis to estimate natural mortality by size groups for yellowfin, bigeye and skipjack tuna in the western Pacific Ocean.
- Maunder et al. (2010) applied a cohort analysis to conventional and archival tag data to estimate age-specific natural mortality for bigeye tuna in the eastern Pacific Ocean.
  - The estimates were highly uncertain and dependent on the reporting rate of archival tags by the longline fleet. The analysis did not use the additional location information available from archival tag data.
- Whitlock et al. (2012) estimated age-specific M for Pacific bluefin tuna using archival tags taking advantage of the additional location information between release and recapture to model movement among areas.
- Integrating the tagging data into the stock assessment model
  - Tag growth-increment data should help resolve age-composition estimates
  - Return rates will improve estimates of total mortality
  - Catch (or effort) data will allow the separation of mortality into M and F
  - Inclusion of indices of abundance to resolve time-series trends in abundance
- Bayliff (1971) provided crude estimate of M for EPO yellowfin tuna from tagging data.
- Recently collected tagging data for yellowfin in the EPO is limited and has not yet been used for estimating natural mortality.

Estimating M inside the stock assessment model

- Lee et al. (2011) showed that M could be estimated reliable for some stocks.
- In some cases the estimates included M that varied with age or sex.
- Bias and variance in estimates of M from actual data is expected to be higher than that found by Lee et al. (2011).
- Estimation of M within the stock assessment model should be improved with the inclusion of tagging data.
- Estimates of M from the stock assessment model will probably be sensitive to the assumptions about growth.

Age, sex, and time specific M

- Several studies have derived empirical relationships of declining M with age or size and differences between males and females
- M is higher for young individuals due to predation and physiological factors.
- M may also increase for older individuals due to the costs of reproduction or other senescent factors
- In general, changes in M for ages younger than observed in the data do not have to be modeled because they only scale the estimated average recruitment.
- Use of predation in multi-species and ecosystem models has been advocated as a way to estimate natural mortality.
- Natural mortality for yellowfin and other tuna has been estimated to vary with size (e.g. Hampton 2000) and age (Whitlock et al. 2012).
- Due to limited aging and gender information for yellowfin in the EPO, a_{max} is not available for each gender.
- Schaefer (1996; 2001) found that the energetic costs of spawning were higher for female yellowfin (0.7% of body weight/day) compared to male yellowfin (0.3% of body weight/day) suggesting that reproduction might cause M to be higher for females.
- Pre-spawning courtship involves both females and males and can last for several hours presumably at a high energetic cost (Margulies at al. 2007).
- Sex ratio data for yellowfin in the EPO favors males at large sizes (Schaefer 1998) suggesting that female M is higher than male M.
- Males mature at shorter lengths (L50% = 69.0 cm, age = 1.3) than do females (L50% = 92.1 cm, age = 2.0) suggesting that males have a higher natural mortality than females based on life history theory.
- Fonteneau and Pallares (2005) suggest that schooling behavioral changes in tuna that occur as tuna age (e.g. disassociation with floating objects) might also influence natural mortality.

YFT M

- The current EPO yellowfin tuna assessment model assumes that M is age and sex-specific (see above).
- It assumes that female M increases after they mature, while male M does not.
- An alternative may be that male M also increases, but at a lower rate than females as indicated by the high energetic cost of extensive pre-spawning courtship (Margulies et al. 2007).
- The change in female M was assumed to occur at 1.5 years (6 quarters) lag after maturity in EPO yellowfin because that is when the sex ratio changes

M for other stocks and species

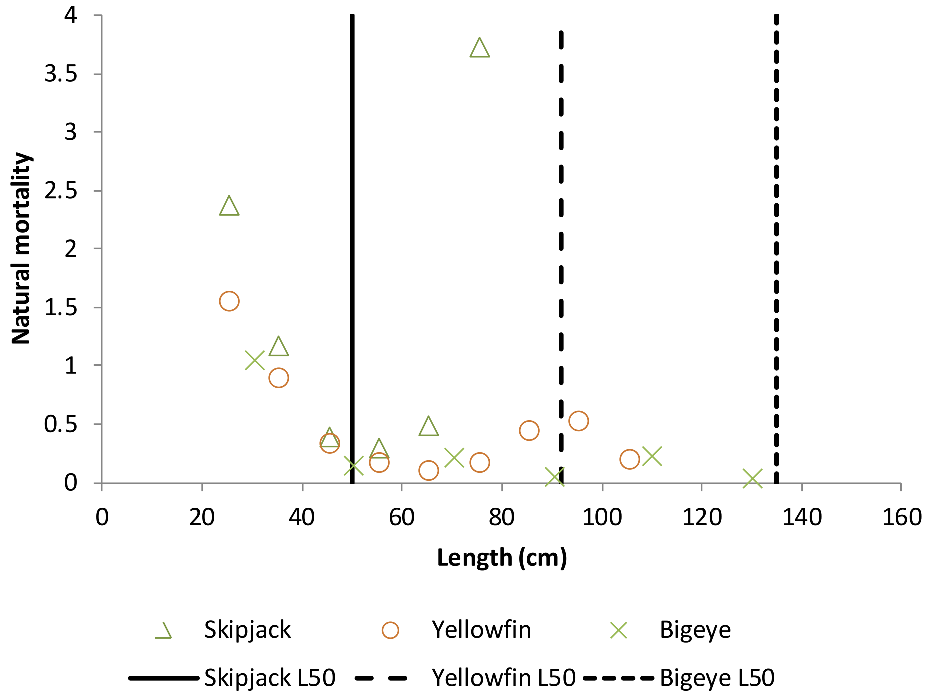
- Hampton (2000) applied tag-attrition analysis to estimate natural mortality by size groups for yellowfin, bigeye and skipjack tuna in the western Pacific Ocean.
- Maunder et al. (2010) applied a cohort analysis to conventional and archival tag data to estimate age- and sex-specific natural mortality for bigeye tuna in the eastern Pacific Ocean.
- Whitlock et al. (2012) estimated age-specific M for Pacific bluefin tuna using archival tags taking advantage of the additional location information between release and recapture to model movement among areas.
- Meta-analysis has been applied to other population dynamics parameters
- Previous approaches using M have focused on correlations with other quantities.
- The main tuna species skipjack, yellowfin, bigeye, albacore, and bluefin have very different life histories (e.g. age and size at maturity)
- Fonteneau and Pallares (2005) argue that because small skipjack, yellowfin, and bigeye mix in the same schools, live in the same habitat, show similar behavior, eat the same prey, and are vulnerable to the same predators, they should have similar levels of natural mortality
- Due to differences in energy expenditure, tropical tunas (skipjack, yellowfin, and bigeye) which spawn continuously may have different patterns of natural mortality than temperate tunas (albacore and bluefin) that spawn seasonally and make large transoceanic migrations.

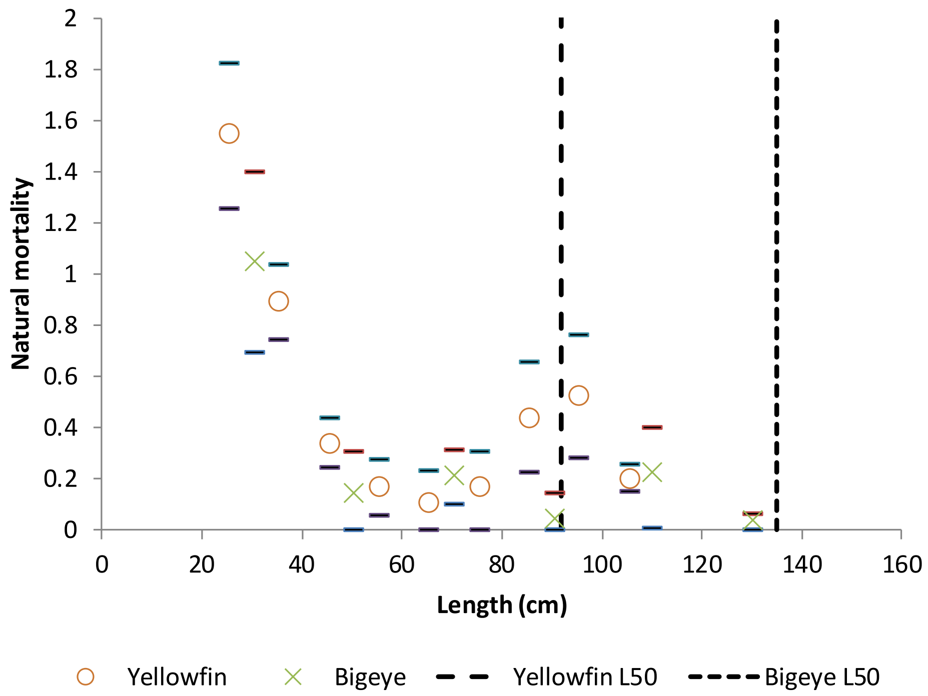
Table 1. Existing estimates of M for Pacific yellowfin.

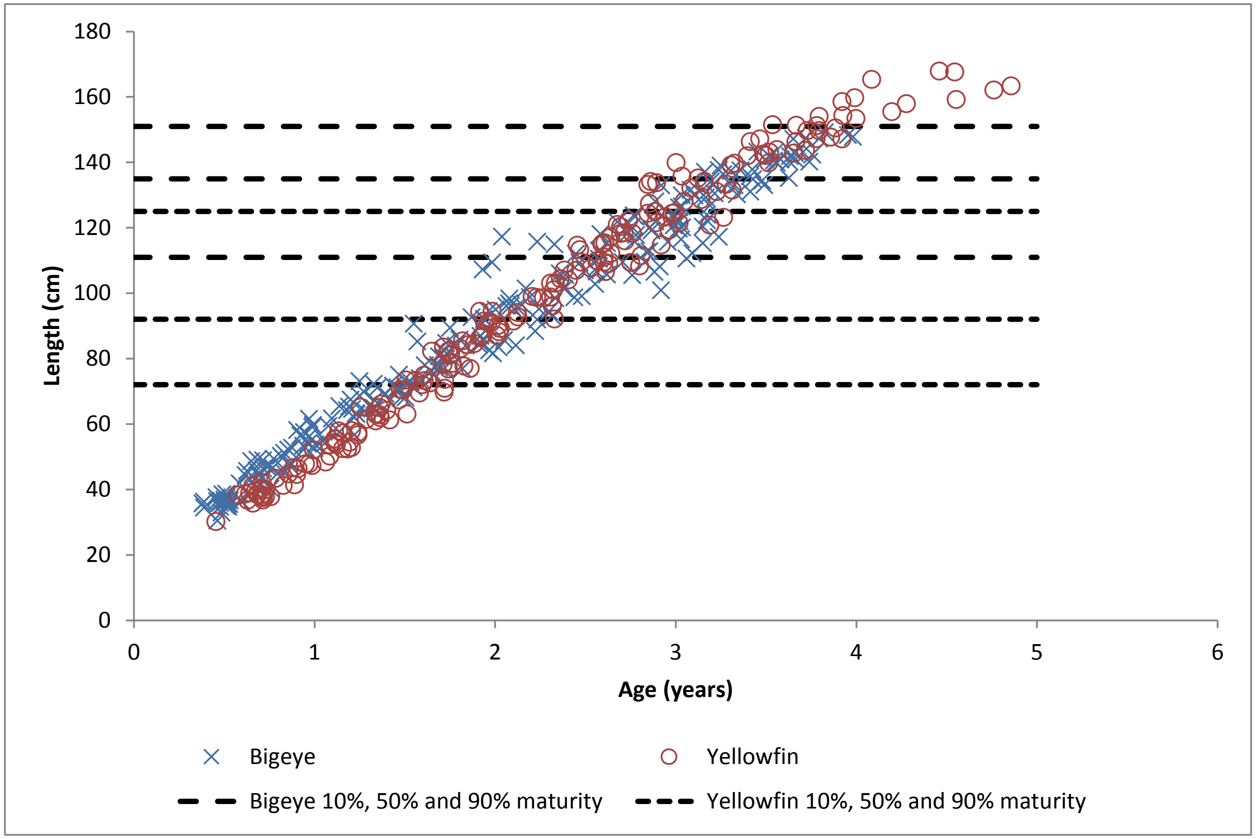
	M estimate[1]	Method	Age range	Region	Source
1.	0.34	Catch curve (sequential recruitment)	1-3 yr	Western and central Pacific	Ishii (1967a,b,1968,1969) (after Cole 1990)
2.	0.91	Catch curve (sequential recruitment)	>4 yr	Western and central Pacific	Ishii (1967a,b,1968,1969) (after Cole 1990)
3.	0.3 or 0.9	Catch curve	2-3 yr	Western and central Pacific	Honma *et. al.* (1971) (after Cole 1990)
4.	1.2	Catch curve	>4 yr	Western and central Pacific	Honma *et. al.* (1971) (after Cole 1990)
5.	2.5	Catch curve	>2 yr	Western Pacific	Honma *et. al.* (1971) (after Suzuki 1991)
6.	1.1	Catch curve	>2 yr	Central Pacific	Honma *et. al.* (1971) (after Suzuki 1991)
7.	0.3	Life history	n.a.	Western and central Pacific	Honma *et. al.* (1971) (after Suzuki 1991)
8.	0.5	Life history	n.a.	Philippines	White (1982) (after Suzuki 1991)
9.	0.6-0.9	Life history	n.a.	Western Pacific	This paper
10.	1.07 (0.92-1.22)[2]	Tag recapture	0.5-2 yr	Western Pacific	SCTB 5/WP.3
11.	0.77 (0.64-0.90)[2]	Catch curve	1-3 yr	Eastern Pacific	Hennemuth (1961) (after Cole 1990)
12.	0.55-1.05	Catch curve	1-3 yr	Eastern Pacific	Schaefer (1967) (after Cole 1990)
13.	<2.0	Tag recapture	1-3 yr	Eastern Pacific	Bayliff (1971) (after Cole 1990)
14.	0.6	Simulation	1-3 yr	Eastern Pacific	Francis (1977) (after Cole 1990)

[1] All estimates are given in units of yr^{-1}.

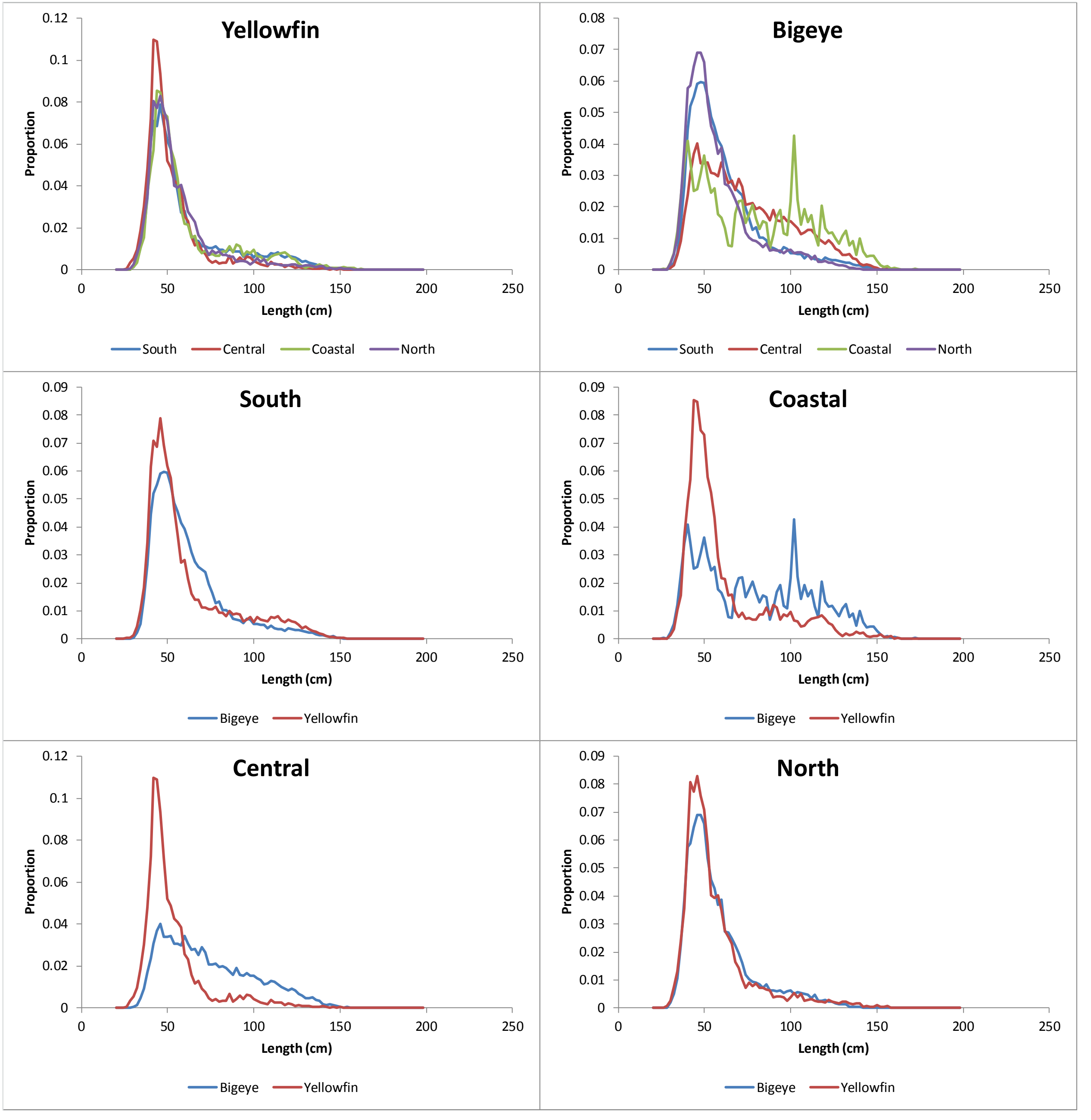
[2] 95% confidence interval.

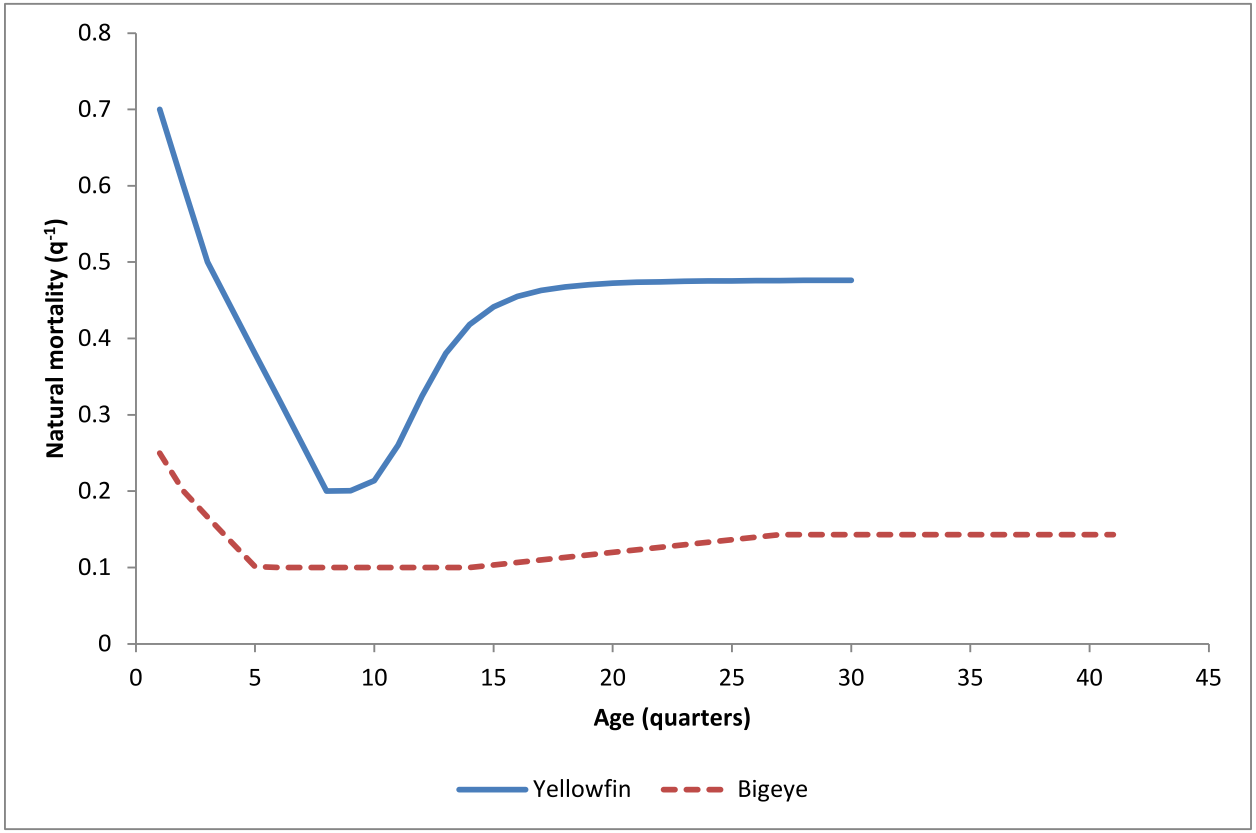

Natural mortality
Length (cm)
Skipjack
Yellowfin
Bigeye
Skipjack L50
Yellowfin L50
Bigeye L50


Natural mortality
Length (cm)
Yellowfin
Bigeye
Yellowfin L50
Bigeye L50

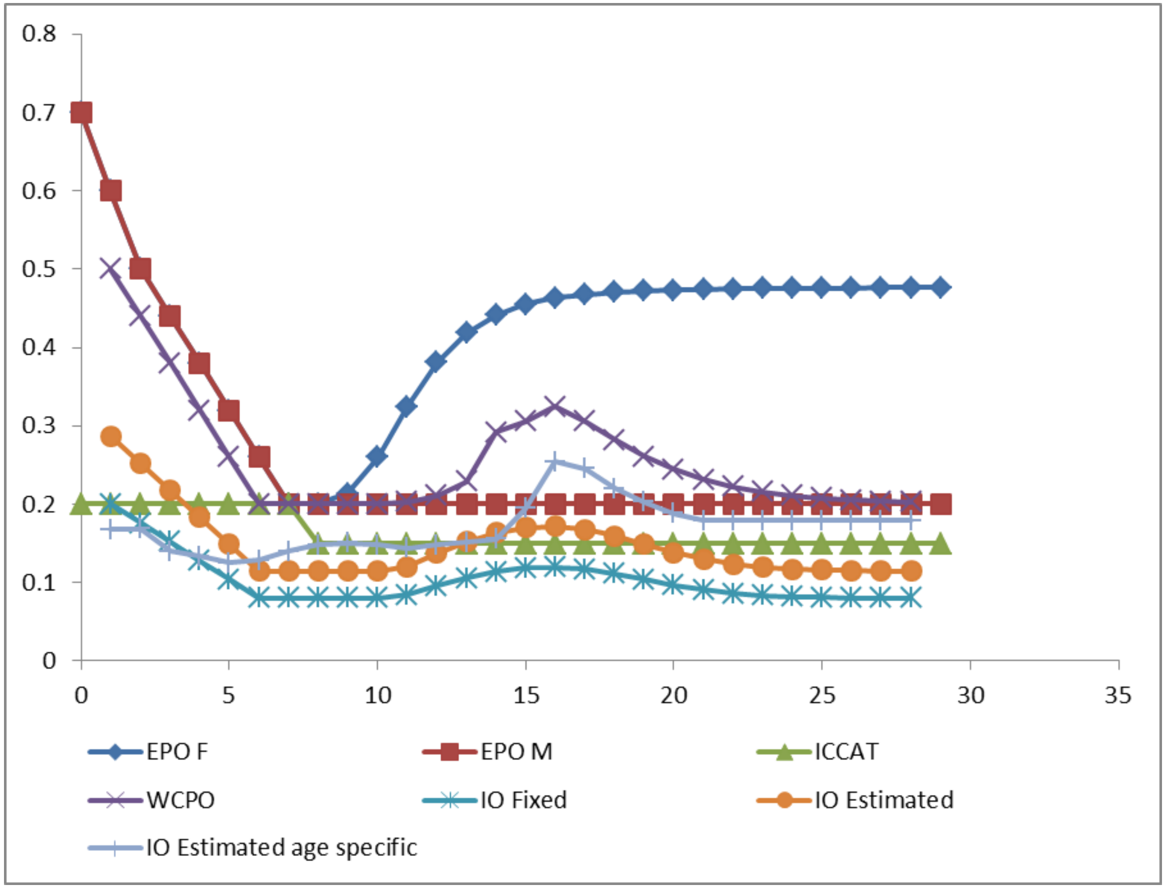


180
160
140
120
100
80
60
40
20
0
Length (cm)
0
1
2
3
4
5
6
Age (years)
Bigeye
Yellowfin
Bigeye 10%, 50% and 90% maturity
Yellowfin 10%, 50% and 90% maturity


Yellowfin
Proportion
0.12
0.1
0.08
0.06
0.04
0.02
0
0
50
100
150
200
250
Length (cm)
South
Central
Coastal
North
Bigeye
Proportion
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Length (cm)
South
Central
Coastal
North
South
Proportion
0.09
Length (cm)
Bigeye
Yellowfin
Coastal
Proportion
Length (cm)
Bigeye
Yellowfin
Central
Proportion
Length (cm)
Bigeye
Yellowfin
North
Proportion
Length (cm)
Bigeye
Yellowfin



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Natural mortality (q^{-1})
0
5
10
15
20
25
30
35
40
45
Age (quarters)
Yellowfin
Bigeye



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
EPO F
EPO M
ICCAT
WCPO
IO Fixed
IO Estimated
IO Estimated age specific

Simulation analysis: method

- (1) The model is fit to the original data based on a pre-specified value for M.
- (2) The model parameters estimated in (1) are used to generate artificial data sets based on the characteristics of the data used when fitting the model
- (3) The model is fit to the simulated data, this time treating M as an estimated parameter.
- (4) Steps (2)–(3) are repeated 8 times.
- (5) Steps (1)–(4) are repeated for a range of values of M.

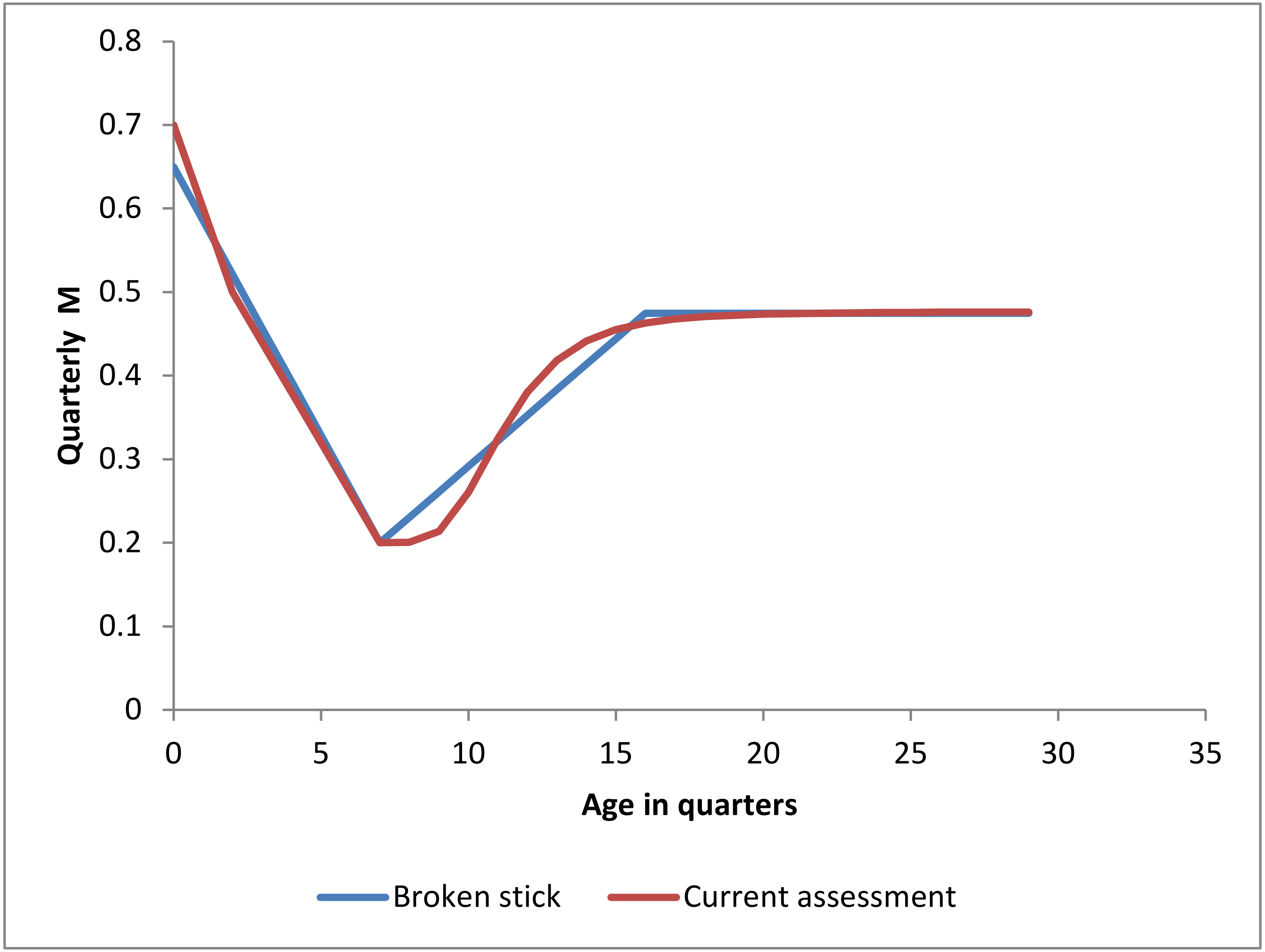
Simulation analysis

- Parameterization
  - parameters of one gender can be made an exponential offset of the other gender or
  - offset of the parameter value for the previous younger age for the same gender.
- Male M an offset of the female M and allow the Male M to change when they mature.
- No period where M is constant before they mature
- Assume that the formulation is adequate for the purposes of our investigation.

3 break broken stick model

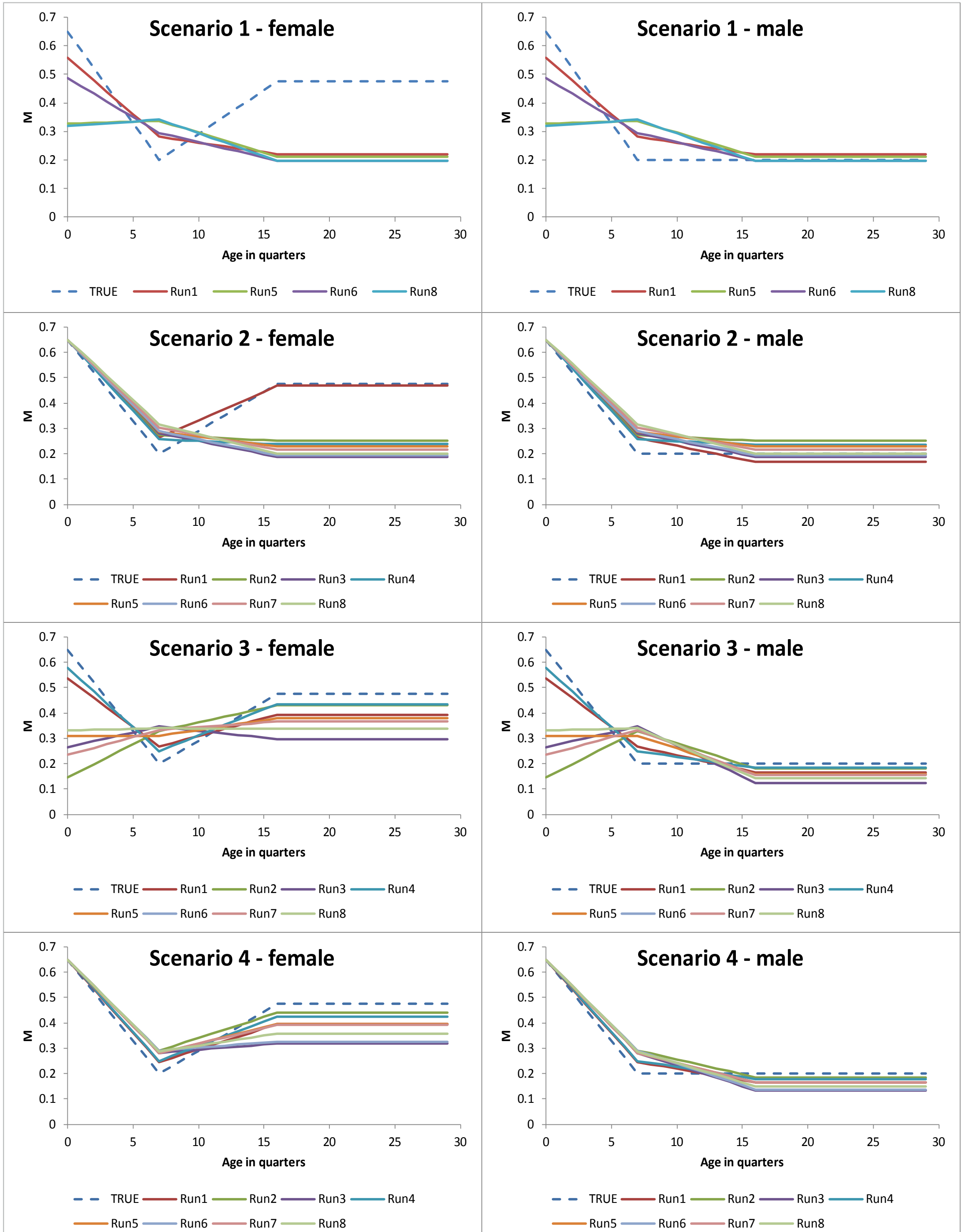
Parameter	Age	Rational	Female	Male Offset (value)
1	0	The smallest age should have the highest M	0.65	0 (0.65)
2	7	The age where predation is assumed to be nominal	0.2	0 (0.2)
3	16	The age when most of the individuals are mature	0.474692203	-0.804349394 (0.2)

M approximation



Estimation scenarios

Scenario	M0	a1	a2	Ma1	Mf	Moffset
A	0.65	7	16	0.2	est	est
B	0.65	7	16	est	est	est
C	est	7	16	est	est	est
D	0.65	7	16	0.2	est	0
E	0.65	7	16	est	est	0
F	est	7	16	est	est	0
G	0.65	7	16	0.2	est	-0.86
H	0.65	7	16	est	est	-0.86
I	est	7	16	est	est	-0.86

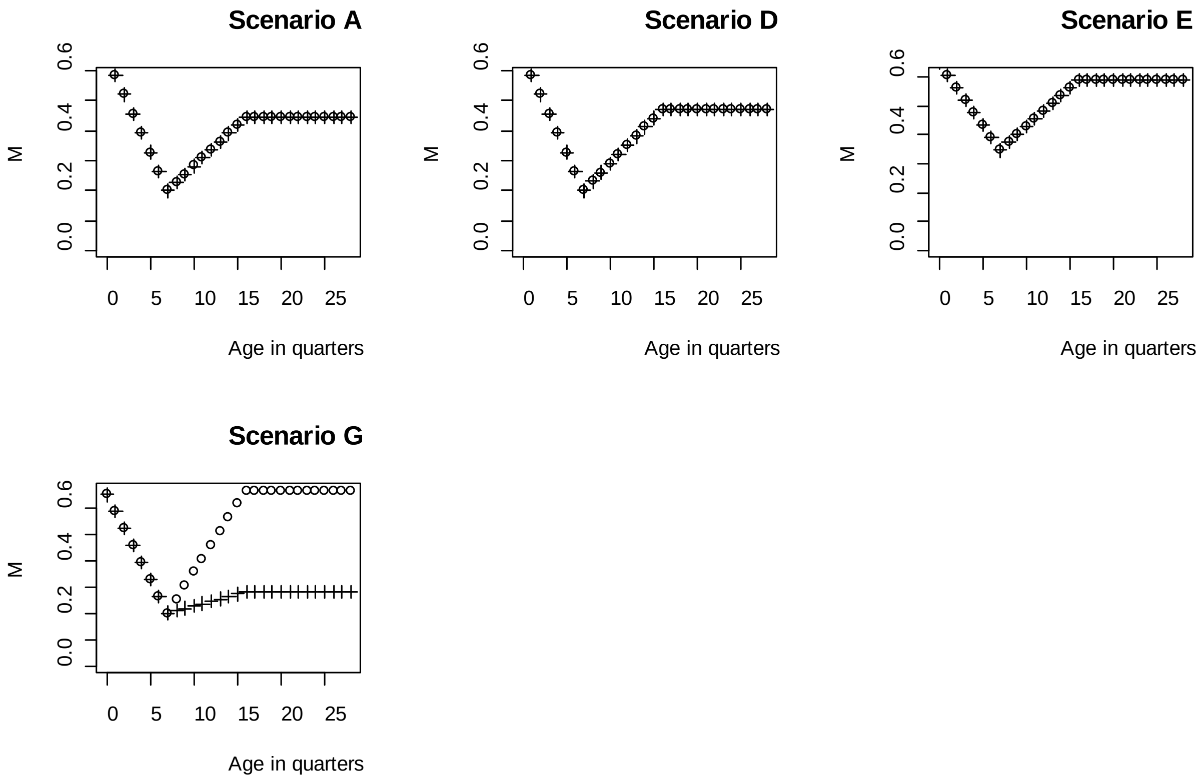

Scenario 1 - female
M
Age in quarters
TRUE Run1 Run5 Run6 Run8
Scenario 1 - male
M
Age in quarters
TRUE Run1 Run5 Run6 Run8
Scenario 2 - female
M
Age in quarters
TRUE Run1 Run2 Run3 Run4
Run5 Run6 Run7 Run8
Scenario 2 - male
M
Age in quarters
TRUE Run1 Run2 Run3 Run4
Run5 Run6 Run7 Run8
Scenario 3 - female
M
Age in quarters
TRUE Run1 Run2 Run3 Run4
Run5 Run6 Run7 Run8
Scenario 3 - male
M
Age in quarters
TRUE Run1 Run2 Run3 Run4
Run5 Run6 Run7 Run8
Scenario 4 - female
M
Age in quarters
TRUE Run1 Run2 Run3 Run4
Run5 Run6 Run7 Run8
Scenario 4 - male
M
Age in quarters
TRUE Run1 Run2 Run3 Run4
Run5 Run6 Run7 Run8

Actual estimates

- The assessment is repeated with the addition that natural mortality is estimated.
- Likelihood values for each data component are presented to determine which components of the data are informative about M.

Estimation scenarios

Scenario	M0	a1	a2	Ma1	Mf	Moffset
A	0.65	7	16	0.2	est	est
B	0.65	7	16	est	est	est
C	est	7	16	est	est	est
D	0.65	7	16	0.2	est	0
E	0.65	7	16	est	est	0
F	est	7	16	est	est	0
G	0.65	7	16	0.2	est	-0.86
H	0.65	7	16	est	est	-0.86
I	est	7	16	est	est	-0.86


Scenario A
Scenario D
Scenario E
Scenario G
M
0.0
0.2
0.4
0.6
0
5
10
15
20
25
Age in quarters

	Aires da Silva and Maunder (2012)	Broken stick M	A	D	E	G
Management quantities						
Msy	262642	263006	307108	326370	9.00E+17	284078
Bmsy	356682	352865	362940	380523	7.00E+17	343565
Smsy	3334	3072	2937	2993	2.00E+15	2506
Bmsy/Bzero	0.31	0.31	0.34	0.34	0.32	0.33
Smsy/Szero	0.26	0.25	0.17	0.17	0.06	0.23
Crecent/msy	0.79	0.78	0.67	0.63	2.30E-13	0.73
Brecent/Bmsy	1.00	1.04	1.44	1.51	2.59	1.31
Srecent/Smsy	1.00	1.07	1.97	2.16	12.63	1.57
Fmultiplier	1.15	1.21	2.22	2.54	2.00E+13	1.83
Negative log likelihoods						
Survey	-148.93	-149.06	-152.37	-154.29	-147.15	-151.26
Length	8443.82	8450.42	8412.02	8401.87	8392.98	8452.89
Recruitment	-5.41	-5.11	-4.30	-4.31	-2.38	-4.70
Total	8289.5	8296.27	8255.37	8243.29	8243.47	8296.94
M estimates						
F0	NA	0.65	0.65	0.65	0.65	0.65
M0	NA	0.65	0.65	0.65	0.65	0.65
F7	NA	0.20	0.20	0.20	0.35	0.20
M7	NA	0.20	0.20	0.20	0.35	0.20
F16	NA	0.47	0.45	0.47	0.59	0.67
M16	NA	0.47	0.45	0.47	0.59	0.28

Management consequences: scenarios

Scenario	M0	a1	a2	Ma1	Mf	Mm
1 (base)	0.65	7	16	0.2	0.474692	0.2
2	0.4875	7	16	0.2	0.474692	0.2
3	0.8125	7	16	0.2	0.474692	0.2
4	0.65	5	16	0.2	0.474692	0.2
5	0.65	9	16	0.2	0.474692	0.2
6	0.65	7	12	0.2	0.474692	0.2
7	0.65	7	20	0.2	0.474692	0.2
8	0.65	7	16	0.15	0.474692	0.2
9	0.65	7	16	0.25	0.474692	0.25
10	0.65	7	16	0.2	0.36	0.2
11	0.65	7	16	0.2	0.59	0.25
12	0.65	7	16	0.2	0.59	0.2
13	0.65	7	16	0.2	0.47	0.25
14	0.65	7	16	0.2	0.47	0.47
15	0.65	7	16	0.2	0.36	0.36
16	0.65	7	16	0.2	0.59	0.59

Management consequences: results

	1 (base)	2	3	4	5	6	7	8
Management quantities								
msy	263006	261563	262799	263005	266059	265228	261792	262720
Bmsy	352865	354251	353424	356394	354529	345392	358630	374742
Smsy	3072	3307	2904	3036	2767	2642	3352	3760
Bmsy/Bzero	0.31	0.32	0.31	0.31	0.31	0.31	0.31	0.31
Smsy/Szero	0.25	0.27	0.24	0.28	0.21	0.27	0.24	0.28
Crecent/msy	0.78	0.79	0.78	0.78	0.78	0.78	0.79	0.79
Brecent/Bmsy	1.04	0.97	1.07	0.99	1.12	1.1	1	0.87
Srecent/Smsy	1.07	0.95	1.14	0.98	1.29	1.18	1	0.81
Fmultiplier	1.21	1.04	1.28	1.09	1.45	1.34	1.14	0.94
Negative log likelihoods								
Survey	-149.06	-144.23	-147.09	-149.27	-149.00	-149.60	-148.68	-148.01
Length	8450.42	8485.20	8454.61	8501.05	8420.06	8482.19	8441.26	8437.51
Recruitment	-5.11	-5.38	-4.71	-5.20	-4.87	-5.13	-5.06	-5.40
Total	8296.27	8335.61	8302.82	8346.6	8266.21	8327.48	8287.54	8284.12

Management consequences: results (cont.)

	9	10	11	12	13	14	15	16
Management quantities								
msy	287360	261392	273786	264759	269449	328890	279372	418320
Bmsy	344966	361537	343390	347458	346037	382797	350161	461123
Smsy	2346	3489	2671	2789	2928	3001	3169	3220
Bmsy/Bzero	0.32	0.31	0.32	0.31	0.32	0.34	0.33	0.35
Smsy/Szero	0.19	0.23	0.24	0.27	0.22	0.17	0.18	0.17
Crecent/msy	0.72	0.79	0.75	0.78	0.77	0.63	0.74	0.49
Brecent/Bmsy	1.34	0.97	1.21	1.09	1.15	1.52	1.25	1.76
Srecent/Smsy	1.78	0.97	1.37	1.15	1.28	2.19	1.53	2.85
Fmultiplier	2.02	1.1	1.58	1.3	1.45	2.58	1.68	3.96
Negative log liklleihoods								
Survey	-152.18	-148.43	-151.39	-149.43	-150.81	-154.39	-152.74	-154.23
Length	8447.82	8440.20	8447.21	8464.68	8433.76	8401.59	8410.23	8410.07
Recruitment	-4.56	-5.05	-4.95	-5.15	-4.95	-4.28	-4.70	-3.93
Total	8291.1	8286.73	8290.88	8310.11	8278.02	8242.93	8252.81	8251.92

Summary

- One of the most influential quantities in fisheries stock assessment and management quantities.
- Indirect approaches based on relationships with life history parameters or maximum observed age are notoriously imprecise or biased.
- M is not constant over age, time, or gender.
- Recent studies estimatiung M inside the stock assessment model show promise (e.g. Lee et al. 2011).
- The ability to estimate M for EPO yellowfin tunais particularly poor given the lack of good aging data.
- Tagging studies have been applied to tuna (e.g. Hampton 2000) and they represent the most promising approach to estimate M for yellowfin tuna in the EPO
- Integrating the tagging data into the stock assessment model should be the gold standard

Recommendations

- Next assessment
  - Use estimates of natural mortality for bigeye and yellowfin tuna from Hampton (2000) for ages less than 80 cm
  - Estimate the female mature natural mortality with the ratio between mature male and mature female natural mortality fixed at levels used in the current assessment.
- Research
  - Investigate integrating the sex composition data into the model to estimate both male and female mature M.
  - Request that priors on M at a given age be implemented in Stock Synthesis.
  - Re-estimate M outside the model using the approach of Harley and Maunder (2003) using both yellowfin and bigeye estimates of M from Hampton (2000).
  - Consider using the historical sex ratio data.
- Data collection
  - Implement a comprehensive tagging program