 Collect. Vol. Sci. Pap. ICCAT, 71(4): 1766-1788 (2015)

AN ASSESSMENT OF THE WESTERN STOCK OF ATLANTIC BLUEFIN TUNA USING A NON-EQUILIBRIUM SURPLUS PRODUCTION MODEL

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SUMMARY

A non-equilibrium surplus production model, used to assess the status of the western Atlantic Bluefin tuna population, indicated that it was dynamically similar in terms of r and K to that of the population assessed by VPA under the high recruitment scenario. The current status in terms of relative biomass and fishing mortality however, was similar to its assessed status under the low recruitment scenario. Sensitivity analyses of the status and dynamics to the indices and component data indicated that, as in past analyses, the most precise and optimistic estimates involve runs including the combined Japanese long line index, which is the longest index and informs the estimation process during the early years of high catches. However, estimates of r and K seemed more reasonable when all indices were involved in parameter estimation. Truncation of the times series impacted the perception of population dynamics more seriously when the early years of high yield or recent years in biomass recovery were excluded.

RÉSUMÉ

Un modèle de production excédentaire en condition de non-équilibre, utilisé pour évaluer l'état de la population du thon rouge de l'Atlantique Ouest, indiquait que son état était dynamiquement identique en termes de r et de K à celui de la population évaluée au moyen de la VPA dans le cadre d'un scénario de recrutement fort. L'état actuel en termes de mortalité par pêche et de biomasse relatives était toutefois similaire à l'état évalué en vertu du scénario de recrutement faible. Une analyse de sensibilité de l'état et des dynamiques par rapport aux indices et aux données des composantes indiquait que, à l'instar des analyses antérieures, les estimations les plus précises et optimistes impliquent des scénarios incluant l'indice palangrier combiné japonais, qui est l'indice le plus long, et étaye le processus d'estimation pendant les premières années de prises élevées. Ceci dit, les estimations de r et de K semblaient plus acceptables lorsque tous les indices étaient utilisés dans l'estimation des paramètres. La troncature de la série temporelle a eu un impact plus fort sur la perception des dynamiques de population lorsque les premières années de production élevée ou les années récentes de récupération de la biomasse étaient exclues.

RESUMEN

Un modelo de producción excedente en no equilibrio, utilizado para evaluar el estado de la población de atún rojo del Atlántico occidental, indicaba que era dinámicamente similar, en términos de r y K, al de la población evaluada mediante VPA en el marco de un escenario de reclutamiento alto. Sin embargo, el estado actual, en términos de biomasa y la mortalidad por pesca relativas, era similar a su estado evaluado en el marco del escenario de reclutamiento bajo. Los análisis de sensibilidad del estado y la dinámica a los índices y a los componentes de datos indicaban que, al igual que en análisis anteriores, las estimaciones más precisas y optimistas implican ensayos que incluyen el índice de palangre japonés combinado, que es el índice más largo y aporta información al proceso de estimación durante los primeros años de capturas elevadas. Sin embargo, las estimaciones de r y K parecían más razonables cuando todos los índices estaban implicados en las estimaciones de parámetros. Truncar la serie temporal influyó de manera más seria en la percepción de la dinámica de la población cuando se excluían los primeros años de elevado rendimiento o los años recientes en la recuperación de la biomasa.

KEYWORDS

Surplus production, Bluefin tuna

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1. Introduction

Currently, the interpretation of the status of the western Bluefin tuna stock is based on outputs from two age structured population models (Anon. 2013) (Lauretta, Kimoto, Porch, & Hanke, 2014)) which differ with respect to the form of the stock-recruitment relationship. Under the two-line model (the low recruitment potential scenario) the average recruitment cannot reach the high levels from the early 1970s, possibly because of an unknown change in the environment. Conversely, under a Beverton-Holt model (the high recruitment potential scenario) the number of recruits is a continuous function of the spawning biomass in the previous year. Based on the 2012 assessment, these divergent scenarios suggest the stock is neither overfished nor subject to overfishing or it is both overfished and subject to overfishing. The challenge for managers is to not only deal with the uncertainties in the biology, data and indices inherent in most stock assessments but to condition their decisions on TAC based on two very different perceptions of the status of the resource.

A solution to this dilemma might be to consider models that make no assumptions about the form of the stock recruitment relationship. Surplus production models satisfy this requirement and are in fact frequently used in ICCAT because of their simplicity and relatively undemanding data needs. The goal then of this paper is to provide a complimentary view of western Atlantic Bluefin stock status through the lens of a non-equilibrium surplus production. Sensitivities to the indices and component data are also explored and an attempt is made to relate the outcomes to those from alternative models that have been applied to the stock in the past.

2. Methods

A Stock-Production model Involving Covariates (ASPIC version 5.34) provided the statistical platform for estimating parameters of a non-equilibrium surplus-production model from the data.

2.1 Data

Catch data (MT) for western Atlantic bluefin tuna (ATW) dating back to 1950 was provided by ICCAT (file t1nc_20131210.xlsx). The catches were current to 2012 and, given that index values were available to 2013, catches for 2013 were estimated to be the average of the 2010 to 2012 values. Catches were divided into contributions by flag (Canada, Japan, Mexico, USA and Other) and gear (see **Table 1**). The catch by flag and gear was aggregated into subsets that matched as closely as possible the gear, area and size composition characteristics of 6 composite catch rate time series derived from 19 standardized indices of abundance provided by CPC's at the 2012 Bluefin tuna Data Preparatory meeting in Madrid.

The subsets were comprised of catches from the following flag-gear-area combinations:

1. ATL: all catch from Japan plus all Canadian longline and US longline not in the Gulf of Mexico. It also includes Atlantic longline catches from flags such as Argentina, Brazil, Chinese Taipei, Cuba, EU, Korea, Norway, Panama, St. Pierre Miquelon and NEI.
2. CAN+: all Canadian catch excluding longline and purse seine.
3. GoMEX: all Gulf of Mexico catch. The sole contributors being the US longline, US rod and reel, US big fish rod reel and Mexican longline gears.
4. PS: all purse seine catches attributed to Canada and USA.
5. US+: all non longline and purse seine catch outside the Gulf of Mexico largely attributed to the handline, rod and reel and harpoon gear types (see **Table 1**).
6. OTH: the remaining non longline catch.

Because the indices with which the catch subsets were paired extend to 2013, the catch for 2013 was estimated by averaging the previous three years.

The 19 catch rate time series were each scaled to have the same average response and combined by merging or averaging to form 6 catch rate time series. Each of these aggregate CPUE series was paired with the appropriate catch subsets above. The 19 CPUEs were combined as follows:

1. Canada combined: the average of the Canadian GSL and SWNS indices when both were available, the available index when only one existed.

2. US combined: a small fish index was created by merging US RR<145, US RR66-114 and US RR115-144. The US RR145-177 index represented medium fish while the merger of the US RR>195 and US RR>177 indices represented the large fish. The large, medium and small fish indices were then averaged to form the combined index.
3. Japan combined: the average of the JLL AREA 2 (WEST), JLL AREA 3 (31+32), JLL AREAS 17+18, JLL Florida Historic and JLL Brazil Historic indices.
4. Gulf of Mexico combined: the average of the GOMPLL 1-6, GOMPLL 1-6 Early and JLL GOM indices.

The composite indices were matched to the catch subsets as follows: model input = {index; catch}.

1. Comb JapLL and Atlantic Catch = {*Japan combined*; *ATL* }
2. no index and all PS catch = {no index; *PS* }
3. Can+ and CAN catch = {*Canada combined*; *CAN+* }
4. US+ and US RR = {*US combined*; *US+* }
5. GoMex LL and GoMex catch = {*Gulf of Mexico combined*; *GoMEX* }
6. no index and other = {no index; OTH}

2.2 Model Runs

The base run, which all other model runs are variants of, included all six of the index/catch inputs described above. The robustness of the interpretation of stock status was tested by rerunning the base with the following modifications:

1. Alternate starting year; {1960, 1965, 1970, 1975}
2. Alternate ending year; {2008}
3. Drop one index and associated catch; {Japan combined = NOJAP, Canada combined = NOCAN, US combined = NOUS, Gulf of Mexico combined = NOMEX}
4. Drop one index and retain catch; { Japan combined = NOJAPB, Canada combined = NOCANB, US combined = NOUSB, Gulf of Mexico combined = NOMEXB }
5. Keep one index; {Japan combined = JAP, Canada combined = CAN, US combined = US, Gulf of Mexico combined = MEX}
6. Drop purse seine catch; {PS}

All runs required starting estimates of the proportion of virgin biomass present at the beginning of the time series and this quantity remained fixed. In 1950 this was 0.95 and for the truncated time series they were: {0.95, 0.7, 0.60, 0.54}. The estimates were based on biomass and carrying capacity (K) estimates from the base model. Estimates of B_1/K and K are proved in **Table 2**.

Data series were weighted the same. The bounds on maximum sustainable yield (MSY) were {1.0000E+03; 1.0000E+05} with a starting estimate of 9,300 MT. The bounds on K were {5.0000E+04 ; 1.5000E+05} with a starting guess of 110,000 MT. Starting estimates for catchability (q) were uniformly 2.0000E-04.

All runs were based on the logistic production model *(Schaefer, 1954; Pella, 1967)*. The fitting of each of the models was conditioned on yield Thus it was assumed that the yield was more precisely known than the relative abundance.

3. Results

3.1 Trends

Trends in catch for the western Bluefin tuna stock (**Figure 1**, **Table 3**) indicate that in 1950 it was lightly exploited by anglers, however, by the early 1960's and until the implementation of strict management measures in the early 1980's the stock experienced large removals by Japanese long liners and Canadian and US purse seiners. The TAC was further limited in the early 2000's and has constrained the catch to present day.

The time series of abundance used to estimate r and K of the production model are shown in **Figure 2** and **Table 4**. The *Comb JapLL* series is the longest, beginning in 1960. It is virtually the only index that informs the estimation process during the periods of high yield that ended in the early 1980's. The remaining indices speak to the population dynamic from the early 1980's onwards. During the fitting process, mild to moderate negative correlations were detected between the *US+* index and the other indices (*Comb JapLL*: -0.06; *Can+*: -0.07; *GoMex LL*: -0.237). Consequently, consideration must be given to the fact that all indices may not represent the abundance of the stock.

Trends in the base model estimates of absolute biomass and fishing mortality rate are shown in **Figure 3**. The relatively large confidence limits on these estimates are typical of surplus productions models (Prager M. H., 1994) which generally estimate the main biological reference points, relative measures of biomass and fishing mortality and ratios of catchability more precisely. Within generous bounds, the stock biomass dropped to half its starting value in response to the high fishing mortality occurring from 1960 – 1982. **Figure 4** indicates that removals exceeded the surplus production in virtually each of those years. Thereafter, the stock has experienced a protracted period of low fishing mortality resulting in a steady recovery in stock biomass.

The relative levels of stock biomass and fishing mortality over the 64 year time series are depicted in the form of a phase plot (**Figure 5**). The stock trajectory passes from a high biomass, low fishing mortality state to a high biomass, overfished state and then briefly transitions to an overfished, low biomass state before controls first reduce the overfishing and then rebuild the stock to the point where it is no longer overfished. For perspective, VPA based estimates of stock status from the 2014 Bluefin tuna assessment (Lauretta, Kimoto, Porch, & Hanke, 2014) are also provided and although they bracket the terminal SPM estimate they are also well outside the distribution of the 1000 bootstrap realizations.

3.2 Stock Status across Scenarios

The sensitivity of estimates of stock status to the indices, the data and the starting year is represented in **Figure 6**, **Figure 7** and **Table 5**. The most precise estimates of relative biomass and relative fishing mortality as well as the most optimistic stock status resulted from scenarios that contained the *Comb JapLL* index. On the other end of the spectrum were runs that did not include the *Comb JapLL* index, were based solely on the *GoMex LL* index or had a starting year that occurred after the large purse seine and long line harvests of the 1960's and early 1970's. All other runs were intermediate to these and were not so much an evaluation of the indices but of the data available for parameter estimation.

The scenarios that included the *Comb JapLL* index, except those excluding data, yielded low estimates of the biomass providing MSY (**Table 6**, **Figure 8**). The corresponding estimates of MSY for these runs were higher than for the others. The higher MSY relative to B_{MSY} implies higher productivity. Runs with lower productivity, and hence lower MSY relative to B_{MSY}, included the base case and runs with starting years before 1971 or without the *GoMex LL* index and associated catch.

The patterns in the estimates of r and K (**Figure 9**) follows what has been described for B_{MSY} and MSY because they are derived from r and K. Nevertheless, it bears re-iterating that the runs with the Comb JapLL index present and not truncated tend to have higher intrinsic rates of population growth and a lower carrying capacity. The relative relationship between scenarios in r-K feature space is shown in **Figure 10** and are related to estimates of r and K from assessments of the stock conducted since 1990 and using age structured production models (ASPM), virtual population assessments (VPA) and non-equilibrium surplus production models (SPM). With the exception of low recruitment scenario estimates of r and K from the 2014 VPA (Lauretta, Kimoto, Porch, & Hanke, 2014) and two SPM models runs that estimate yield from effort (Prager & Scott, 1993), estimates of r tend to be more similar with scenarios like the base case. These tend to involve all the indices, though they may be missing minor amounts of the data or have alternative starting years earlier than 1971.

Table 7 provides a comparison of MSY, relative biomass and relative fishing mortality estimates for western Bluefin tuna cited in the literature with the estimates from the base case ASPIC model. It is important to note that in some cases it was necessary to derive these values from the information that was given or extract them from figures. The cited assessments would have been incredibly more useful had they reported on an established set of benchmarks and reference points. Based on what is summarized here, there is a common interpretation that the stock was overfished and subject to overfishing for assessments conducted in the early 1990s regardless of what model was used, the number of indices or the length of the time series. There is generally a broader disagreement over the level of MSY even within a class of models. In the case of (Restrepo, 1997), it was noted that including an 8^{th} index, corresponding to long line catch rates of large Bluefin tuna in the western Atlantic for the 1960s and 1970s, resulted in an improved overall fit. (Butterworth & Punt, 1992) also report that the inclusion of a large fish index based on Japanese long line effort affected the interpretation of the status of the resource. With the index the stock is large and unaffected by the fishery. They also note that in the derivation of the index, records with no catch were excluded by the authors.

More recently we observe that the stock is perceived to be much healthier than in the early 1990s even under the less optimistic high recruitment scenario.

4. Conclusions

- A non-equilibrium surplus production model provides an assessment of the resource that lies between the assessed statuses based on high and low recruitment scenarios from a VPA.
- As in past analyses the most precise and optimistic stock status involves runs including the Japanese long line index which is the longest index and informs the estimation process during the early years of high catches.
- While including the *Comb JapLL* index improved stock status, estimates of r and K seemed more reasonable when all indices were involved in parameter estimation.
- It is important to use as long a time series of catch and abundance data as possible.
- Catch only and SPM models are providing similar interpretations of stock status

5. Recommendations

- Consider the benefit of using a GLM approach for combining indices.
- Consider model fit when comparing scenarios.
- Determine sensitivity to terminal years in the series.
- Project biomass under various TACs for the acceptable runs.

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Table 1. Gear reported to have caught western Bluefin tuna between 1950 and 2012.

Gear	*Canada*	*Japan*	*Mexico*	*USA*	*Other*
Gillnet: drift net	Yes	Yes		Yes	Yes
Hand Line				Yes	Yes
Harpoon: Traditional	Yes			Yes	
Harpoon: Electric	Yes				
Longline	Yes	Yes	Yes	Yes	Yes
Longline: Bottom or Deep				Yes	
Longline: Foreign based		Yes			Yes
Longline: Home based	Yes	Yes			Yes
Longline: Surface	Yes				
Longline: Targeting Swordfish					Yes
Purse Seine	Yes			Yes	
Purse seine: catching large fish				Yes	
Purse seine: catching small fish				Yes	
Rod and Reel	Yes			Yes	Yes
Rod and Reel (catching large fish)	Yes			Yes	
Rod and Reel (catching small fish)				Yes	
Handline SPORT (recreational)				Yes	
Tended line	Yes				
Trap	Yes			Yes	
Troll	Yes				
Trawl		Yes		Yes	Yes
Unclassified gears	Yes	Yes		Yes	Yes

Table 2. Estimates of the fraction of virgin biomass available at the start of the time series and the carrying capacity (MT) for all scenarios. Confidence intervals are the 95% bootstrap values.

Run	B_1/K			K		
	Estimate	$L_{95\%}CI$	$U_{95\%}CI$	*Estimate*	$L_{95\%}CI$	$U_{95\%}CI$
JAP	0.95	0.95	0.95	30185.05	25797.33	42862.14
JAPB	0.95	0.95	0.95	30439.4	25469.15	41839.4
NOCANB	0.95	0.95	0.95	30499.17	19208.12	41467.9
NOUSB	0.95	0.95	0.95	30549.96	18977.44	41639.95
2008	0.95	0.95	0.95	31044.76	22164.79	43062.64
NOMEXB	0.95	0.95	0.95	31409.22	25767.41	43724.2
NOUS	0.95	0.95	0.95	31935.05	27099.71	41363.07
JAPC	0.95	0.95	0.95	32467.4	26170.66	47368.54
NOCAN	0.95	0.95	0.95	34396.9	31429.53	42962.87
NOJAP	0.95	0.95	0.95	43070.88	33352.39	53614.04
CAN	0.95	0.95	0.95	58176.77	49363.79	75954.26
1975	0.54	0.54	0.54	58830.67	50934.49	78020.84
NOPURSE	0.95	0.95	0.95	59484.72	44106.3	82299.69
MEX	0.95	0.95	0.95	84597.99	59715.98	119505.5
NOJAPB	0.95	0.95	0.95	90955.89	70611.22	114678.8
US	0.95	0.95	0.95	93054.03	28229.61	220687.6
1965	0.7	0.7	0.7	102707.1	54243.17	145632.7
NOMEX	0.95	0.95	0.95	106282.5	62018.52	192099
1960	0.95	0.95	0.95	107884.6	70949.14	142726.4
1970	0.506874	0.348931	0.704185	110000	110000	110000
BASE	0.95	0.95	0.95	113743.7	71493.87	190598.2

Table 3. Yield (MT) time series used in the analysis. The sum across the columns equals the total catch for the western Bluefin tuna stock from 1950 to 2013.

Year	*Atlantic*	*PS*	*CAN+*	*US+*	*GoMEX*	*OTH*
1950	0.0	1.0	432.0	574.0	0.0	0.0
1951	0.0	100.0	299.0	697.0	0.0	0.0
1952	7.0	0.0	368.0	254.0	0.0	0.0
1953	1.0	0.0	201.0	882.0	0.0	0.0
1954	0.0	55.0	175.0	593.0	0.0	0.0
1955	5.0	0.0	133.0	406.0	0.0	0.0
1956	0.0	0.0	40.0	207.0	0.0	0.0
1957	46.0	0.0	47.0	453.0	0.0	0.0
1958	72.0	138.0	38.0	959.0	0.0	0.0
1959	283.0	781.0	93.0	413.0	0.0	0.0
1960	340.0	277.0	37.0	378.0	0.0	0.0
1961	373.0	903.0	120.0	224.0	0.0	0.0
1962	1351.0	3768.0	177.0	503.0	0.0	0.0
1963	6558.0	5770.0	319.0	1191.0	0.0	0.0
1964	12410.0	5150.0	417.0	694.0	0.0	0.0
1965	9469.0	3331.0	175.0	1196.0	0.0	0.0
1966	3085.0	1006.0	198.0	3801.0	0.0	0.0
1967	3126.0	2082.0	230.0	502.0	0.0	0.0
1968	1665.0	687.0	281.0	543.0	0.0	0.0
1969	593.0	1118.0	363.0	938.0	0.0	0.0
1970	268.0	4288.0	281.0	629.0	0.0	0.0
1971	1390.0	3769.0	147.0	1285.0	0.0	0.0
1972	339.0	2011.0	217.0	1358.0	0.0	23.0
1973	1127.0	1656.0	383.0	676.0	0.0	29.0
1974	949.0	960.0	665.0	2780.0	0.0	39.0
1975	1562.4	2320.0	350.0	816.0	0.0	24.0
1976	3069.0	1582.0	514.0	681.0	0.0	37.0
1977	3753.4	1502.0	674.0	752.0	0.0	14.0
1978	3219.1	1230.0	429.0	859.0	0.0	28.0
1979	3691.0	1381.0	245.0	916.0	0.0	22.0
1980	3972.5	758.0	324.0	737.0	0.0	10.0
1981	3808.0	910.0	320.0	642.0	70.0	20.0
1982	360.0	232.0	291.0	545.0	0.0	14.0
1983	829.0	384.0	433.0	896.0	0.0	0.0
1984	769.0	401.0	264.0	792.0	54.0	0.0
1985	1147.0	377.0	142.0	915.0	87.0	1.0
1986	1161.0	360.0	41.0	643.2	111.0	0.0
1987	1097.7	367.0	50.0	846.3	141.3	1.0
1988	1306.0	383.0	289.0	748.0	167.3	3.0
1989	724.1	385.0	580.0	973.0	94.5	2.0
1990	702.7	384.0	434.0	1092.0	153.4	14.0
1991	838.0	237.0	479.0	1168.0	184.2	14.0

1992	773.0	300.0	434.0	648.5	112.0	14.0
1993	729.0	295.0	434.0	853.0	54.0	2.0
1994	565.7	301.0	387.0	760.2	56.0	43.0
1995	571.4	249.0	572.0	989.0	35.0	9.0
1996	659.0	245.0	575.0	976.0	54.6	4.0
1997	511.0	250.0	497.0	1048.3	26.0	2.0
1998	861.0	249.0	579.0	940.0	26.0	2.0
1999	1013.5	248.0	555.6	891.6	62.0	1.0
2000	1007.6	275.2	548.3	870.8	72.0	1.0
2001	684.8	195.9	517.0	1355.8	29.9	1.0
2002	895.4	207.7	587.7	1582.6	44.7	0.5
2003	342.2	265.4	542.8	1078.8	76.0	0.3
2004	664.7	31.8	509.0	759.0	160.1	0.0
2005	427.6	178.3	563.4	458.6	128.6	0.0
2006	612.2	3.6	686.8	406.6	102.2	0.0
2007	431.9	27.9	433.1	656.5	88.4	0.0
2008	645.8	0.0	545.9	689.0	118.9	0.0
2009	451.7	11.4	468.6	926.1	121.5	0.3
2010	651.7	0.0	440.5	713.9	70.3	0.0
2011	918.3	0.0	398.0	663.3	26.9	0.3
2012	541.5	1.7	428.3	621.9	156.7	0.4
2013	703.8	0.6	422.3	666.3	84.6	0.2

Table 4. Western Atlantic Bluefin tuna indices of abundance.

Year	*Comb Jap LL*	*Can+*	*US+*	*GoMex LL*
1950	-99.00	-99.00	-99.00	-99.00
1951	-99.00	-99.00	-99.00	-99.00
1952	-99.00	-99.00	-99.00	-99.00
1953	-99.00	-99.00	-99.00	-99.00
1954	-99.00	-99.00	-99.00	-99.00
1955	-99.00	-99.00	-99.00	-99.00
1956	-99.00	-99.00	-99.00	-99.00
1957	-99.00	-99.00	-99.00	-99.00
1958	-99.00	-99.00	-99.00	-99.00
1959	-99.00	-99.00	-99.00	-99.00
1960	0.58	-99.00	-99.00	-99.00
1961	0.70	-99.00	-99.00	-99.00
1962	2.42	-99.00	-99.00	-99.00
1963	4.59	-99.00	-99.00	-99.00
1964	1.88	-99.00	-99.00	-99.00
1965	1.43	-99.00	-99.00	-99.00
1966	1.05	-99.00	-99.00	-99.00
1967	0.29	-99.00	-99.00	-99.00
1968	0.39	-99.00	-99.00	-99.00
1969	0.12	-99.00	-99.00	-99.00
1970	0.01	-99.00	-99.00	-99.00
1971	0.34	-99.00	-99.00	-99.00
1972	-99.00	-99.00	-99.00	-99.00
1973	-99.00	-99.00	-99.00	-99.00
1974	-99.00	-99.00	-99.00	1.11
1975	1.26	-99.00	-99.00	0.61
1976	0.98	-99.00	-99.00	0.77
1977	2.22	-99.00	-99.00	1.05
1978	1.01	-99.00	-99.00	1.01
1979	1.26	-99.00	-99.00	1.48
1980	1.23	-99.00	0.80	1.33
1981	1.39	1.14	0.40	0.64
1982	1.44	0.52	2.10	-99.00
1983	0.92	1.33	1.96	-99.00
1984	1.00	0.73	1.25	-99.00
1985	1.12	0.18	0.74	-99.00
1986	0.49	0.21	0.64	-99.00
1987	1.08	0.28	0.87	1.49
1988	0.98	0.95	0.96	0.72
1989	0.79	0.96	0.88	1.11

1990	0.68	0.73	0.76	0.87
1991	0.68	0.78	1.04	1.45
1992	0.90	1.12	0.86	0.35
1993	0.86	0.71	1.03	0.71
1994	0.91	0.49	0.61	0.52
1995	0.89	0.68	1.40	0.49
1996	1.53	0.33	2.13	0.29
1997	0.93	0.29	1.52	0.53
1998	0.55	0.52	1.42	0.56
1999	0.66	0.75	1.69	0.96
2000	0.74	0.38	1.27	1.40
2001	0.77	0.62	2.21	0.80
2002	0.95	0.80	3.01	0.75
2003	0.91	1.19	0.72	1.36
2004	0.66	0.94	1.83	1.22
2005	0.62	1.00	1.73	0.93
2006	1.05	1.10	1.23	0.65
2007	0.94	1.48	1.12	0.86
2008	0.82	1.46	1.07	1.98
2009	1.20	1.66	0.51	1.66
2010	0.53	4.49	1.40	1.40
2011	2.25	2.14	1.33	1.15
2012	3.13	2.93	1.08	2.11
2013	2.27	2.35	1.05	0.68

Table 5. Estimated relative biomass and fishing mortality for all scenarios with 95% bootstrap confidence intervals.

Run	$B./B_{MSY}$			$F./F_{MSY}$		
	Estimate	$L_{95\%}CI$	$U_{95\%}CI$	*Estimate*	$L_{95\%}CI$	$U_{95\%}CI$
MEX	0.989515	0.606365	1.834739	0.452933	0.164576	0.709799
NOJAPB	1.065792	0.74208	1.535323	0.430885	0.292919	0.608799
1975	1.129159	0.917922	1.333782	0.486172	0.403312	0.613286
NOJAP	1.190412	0.908947	1.596286	0.396758	0.291922	0.522235
CAN	1.470618	1.105481	1.713549	0.227178	0.168235	0.325932
1970	1.500759	0.90771	1.832326	0.317936	0.15578	0.543955
NOPURSE	1.552641	1.197394	1.727215	0.346884	0.249822	0.513803
BASE	1.649747	1.221306	1.821663	0.257795	0.170543	0.453479
1960	1.676647	1.260498	1.822309	0.249641	0.170854	0.436765
1965	1.733965	1.205824	1.972491	0.228727	0.027421	0.45993
NOMEX	1.741129	1.255883	1.862551	0.189381	0.121171	0.363975
US	1.795587	0.648184	1.990494	0.188764	0.009488	0.741404
JAPC	1.902206	1.86083	1.915869	0.098704	0.084814	0.139382
2008	1.902928	1.8682	1.919056	0.101443	0.082557	0.138065
NOMEXB	1.904312	1.869996	1.916235	0.096725	0.084513	0.130916
NOUSB	1.906204	1.874881	1.927239	0.094827	0.073078	0.126182
NOCANB	1.906479	1.875965	1.927196	0.094564	0.073123	0.125117
JAPB	1.906994	1.875886	1.917199	0.093877	0.083448	0.124842
JAP	1.907149	1.871912	1.916176	0.093842	0.084576	0.129199
NOCAN	1.924219	1.904232	1.930262	0.073561	0.068176	0.091103
NOUS	1.929739	1.903753	1.940259	0.069035	0.059149	0.093057

Table 6. Estimated benchmarks (MT) for all scenarios with 95% bootstrap confidence intervals.

Run	B_{MSY}			*MSY*		
	Estimate	$L_{95\%}CI$	$U_{95\%}CI$	*Estimate*	$L_{95\%}CI$	$U_{95\%}CI$
JAP	15092.53	12898.67	21431.07	10546.7	7807.246	11646.06
JAPB	15219.7	12734.58	20919.7	10486.28	8021.067	11730.53
NOCANB	15249.58	9604.058	20733.95	10470.1	8095.58	13392.77
NOUSB	15274.98	9488.719	20819.98	10457.74	8082.275	13457.21
2008	15522.38	11082.39	21531.32	10337.78	7850.73	12593.24
NOMEXB	15704.61	12883.71	21862.1	10251.21	7743.887	11654.31
NOUS	15967.53	13549.85	20681.53	8458.464	6364.63	9814.092
JAPC	16233.7	13085.33	23684.27	9997.299	7247.269	11550.1
NOCAN	17198.45	15714.77	21481.44	9177.367	7489.194	9870.213
NOJAP	21535.44	16676.19	26807.02	2569.754	2307.741	2954.335
CAN	29088.38	24681.9	37977.13	5867.061	4757.11	6798.485
1975	29415.33	25467.24	39010.42	3529.905	3239.505	3750.945
NOPURSE	29742.36	22053.15	41149.85	3223.913	2827.764	4006.758
MEX	42298.99	29857.99	59752.74	4460.012	3531.805	6279.43
NOJAPB	45477.94	35305.61	57339.41	4166.866	3647.2	5025.807
US	46527.01	14114.8	110343.8	5596.045	3262.627	99999.57
1965	51353.55	27121.59	72816.34	4747.422	3444.322	35026.48
NOMEX	53141.24	31009.26	96049.5	4775.953	3398.019	6969.74
1960	53942.28	35474.57	71363.2	4524.847	3520.988	6067.989
1970	55000	55000	55000	4111.007	3339.479	6621.739
BASE	56871.87	35746.94	95299.08	4447.2	3435.206	6069.664

Table 7. Estimated benchmarks and references for the western Bluefin tuna stock derived by a number of authors. Year refers to the catch series data on which the analysis was based while Model identifies the run within the source document.

Year	*Model*	*MSY*	*relB*	*relF*	*Source*
1960 -1993	ASPM, 8 index fit	~4000	0.1	3.5	Restrepo (1997)
1970 -1993	ASPM, 7 index fit	~1000			Restrepo (1997)
1950 - 1995	ASPM, base	5074	0.074		Germont & Butterworth (1999)
1960 -1990	SPM, estimated catch, 1 index	3920	0.167	4.68	Prager & Scott (1993)
1960 -1990	SPM, estimated effort, 1 index	8179	0.062	4.25	Prager & Scott (1993)
1960 -1990	SPM, estimated effort, split index	7281	0.106	3.06	Prager & Scott (1993)
1960-1989	ASPM	2657	0.126		Butterworth & Punt (1992)
1990-2006	ASBSPM	5352	0.102	5.94	McAllister & Carruthers (2007)
1970–2011	VPA, base, low recruitment	2634	1.4	0.61	Anon. (2013)
1970–2011	VPA, base, high recruitment	6472	0.19	1.57	Anon. (2013)
1970–2013	VPA, base, low recruitment	3050	2.3	0.35	Anonymous (2014)
1970–2013	VPA, base, high recruitment	5316	0.48	0.86	Anonymous (2014)
1950 – 2013	Catch MSY, low resilience	4739	1.65	0.24	Martell and Froese (2012)
1950 – 2013	Catch MSY, high resilience	5311	1.78	0.20	Martell and Froese (2012)
1950 – 2013	SPM, base	4447	1.65	0.26	This paper

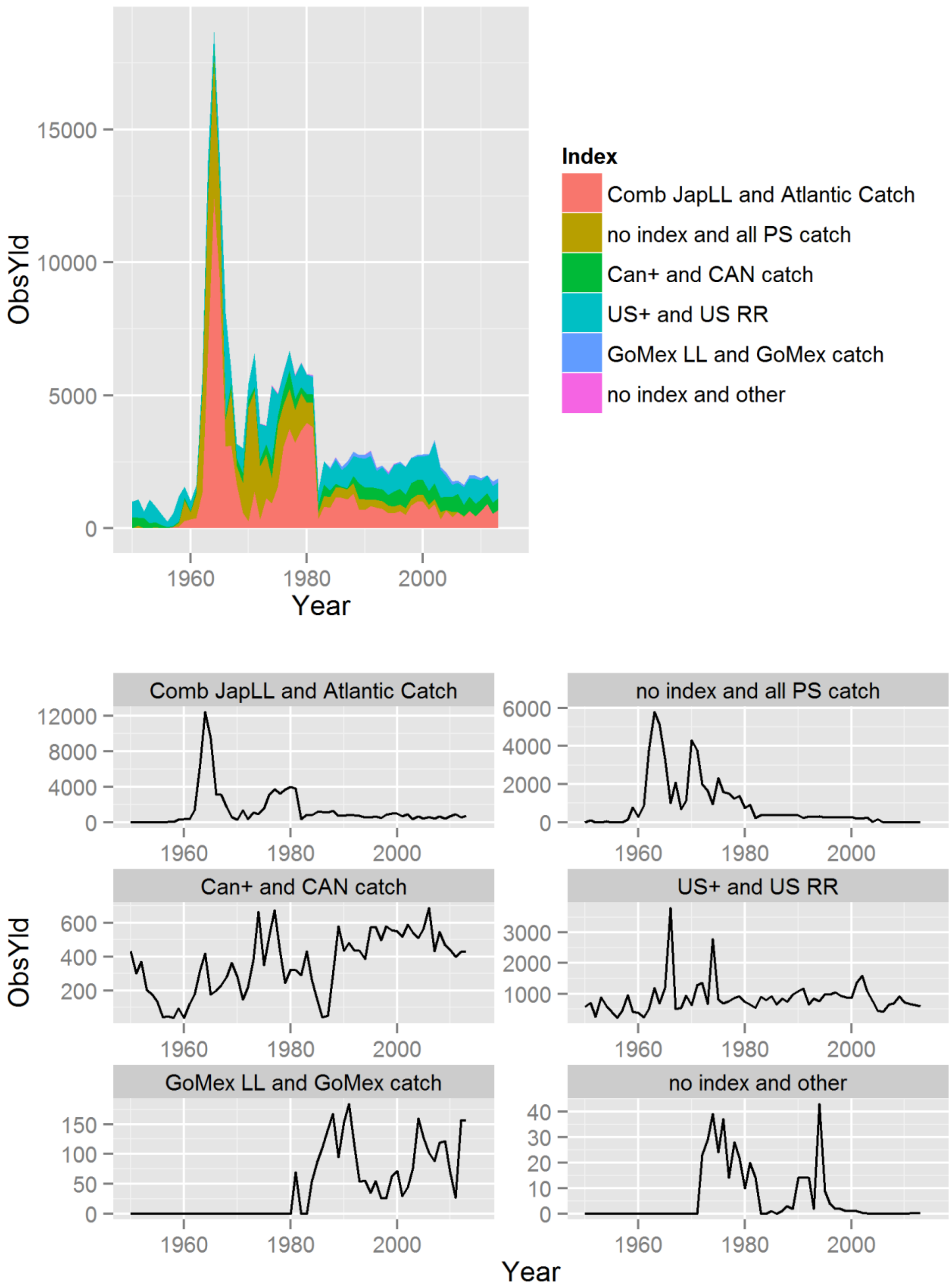

Figure 1. Trend in total western Bluefin tuna catch from 1950 to 2013 (top). Lower panels show the trends in catch for subsets of the data corresponding with unique combinations of flag, fleet and area (see text for details).

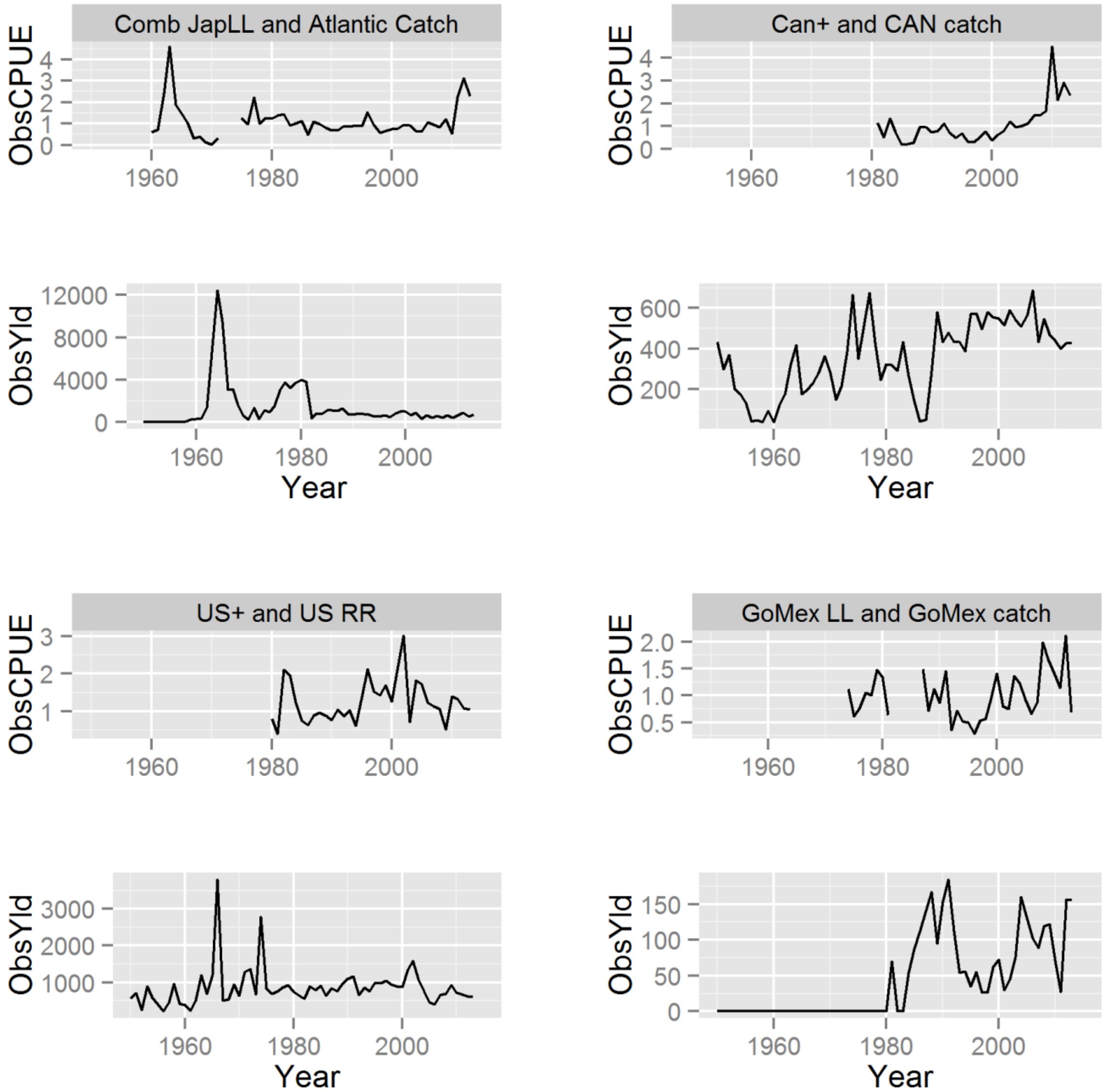

Figure 2. Catch rate time series and catch (MT) for the Japan combined index with ATL catch (top left), Canada combined index with CAN+ catch (top right), US combined index with US+ catch (bottom left) and Gulf of Mexico combined index with GoMEX catch (bottom right).

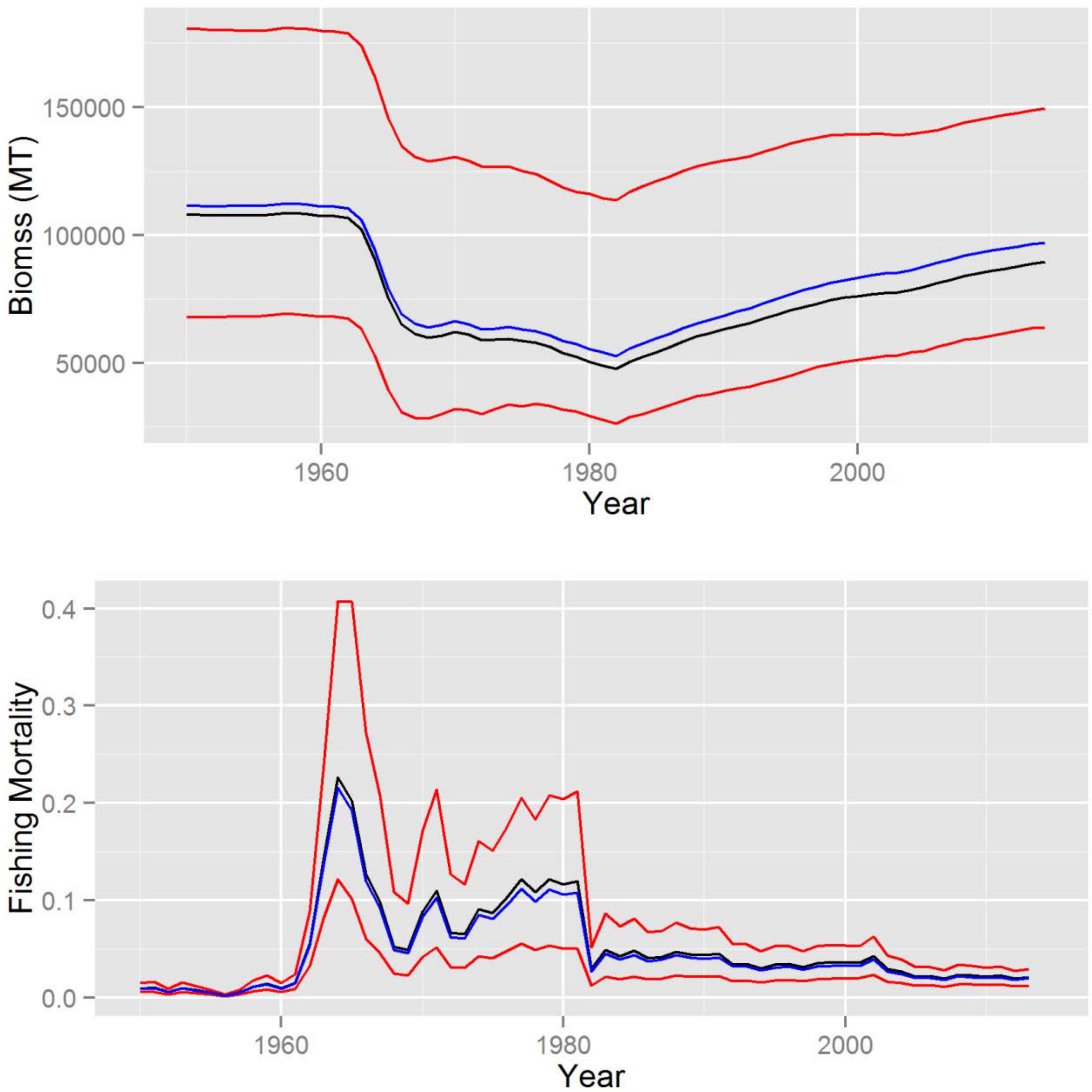

Figure 3. Base case trends in stock biomass (top) and total fishing mortality (bottom) with 95th percentile bootstrap confidence intervals. The blue line represents the biased corrected estimates.

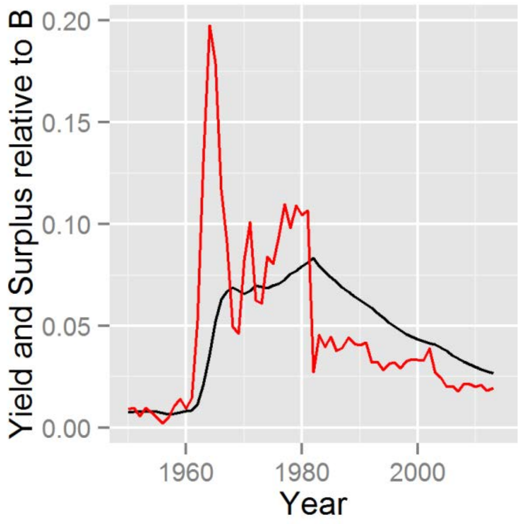

Figure 4. Base case trends in catch (red) and surplus production (black) as a fraction of total stock biomass.

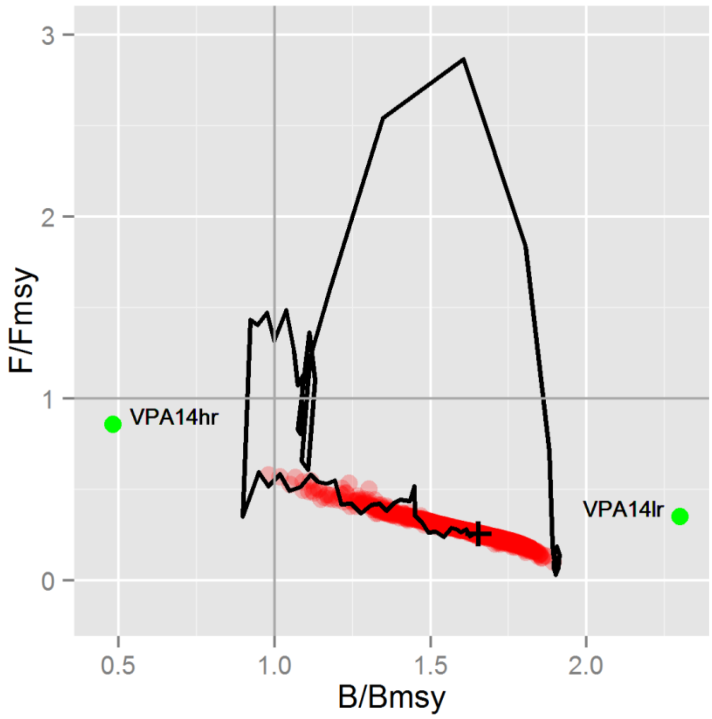

Figure 5. Base case trajectory of the unbiased estimates of relative biomass and relative fishing mortality. The terminal year's estimate is represented by "+" and the distribution of 1000 bootstrap realizations is shown in red. The green points are the relative biomass and fishing mortality estimates from the 2014 Bluefin tuna stock assessment for the high (hr) and low (lr) recruitment scenarios (Lauretta, Kimoto, Porch, & Hanke, 2014).

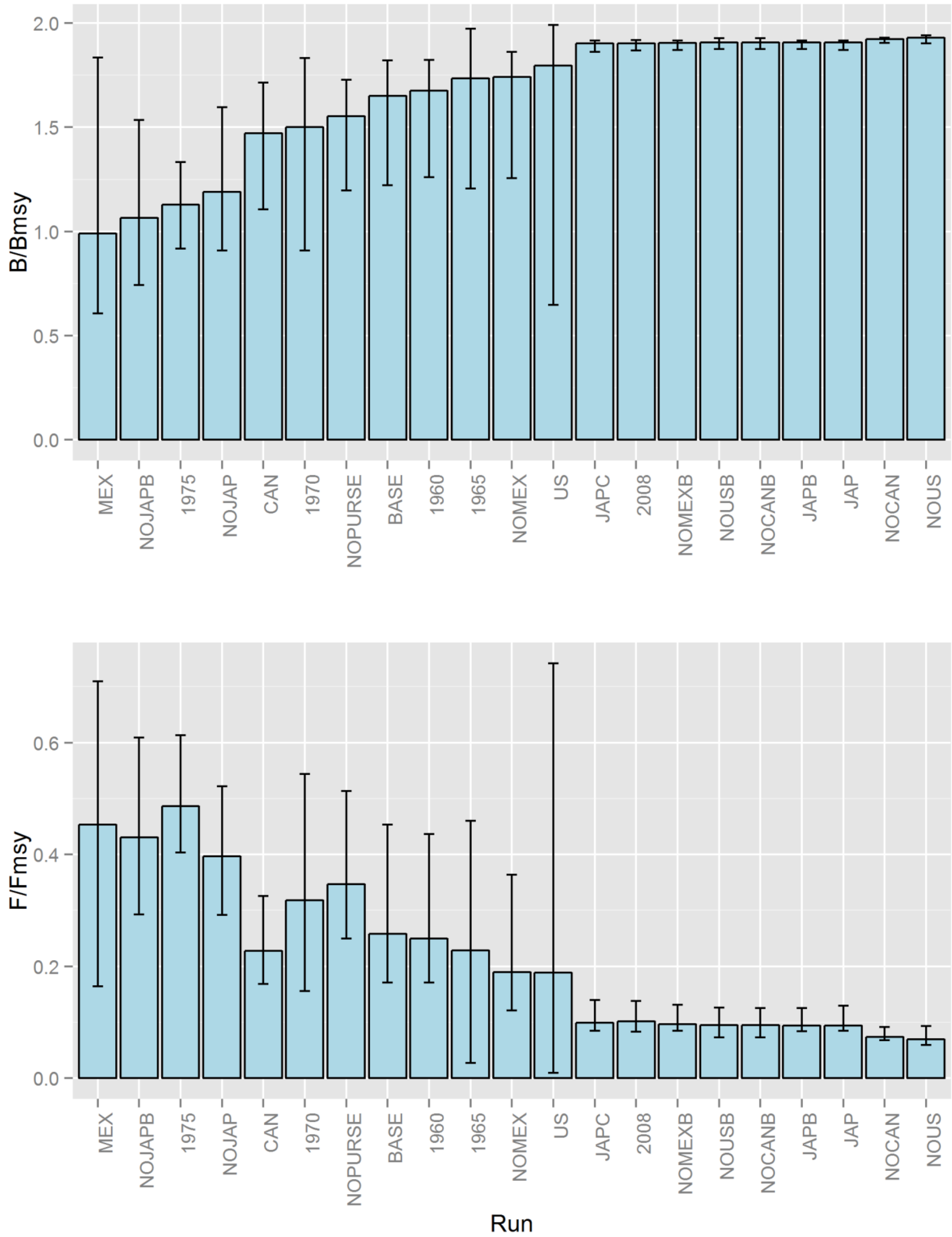

Figure 6. Current relative biomass and relative fishing mortality estimates for all scenarios ordered according to increasing relative biomass. 95% bootstrap confidence intervals are given.

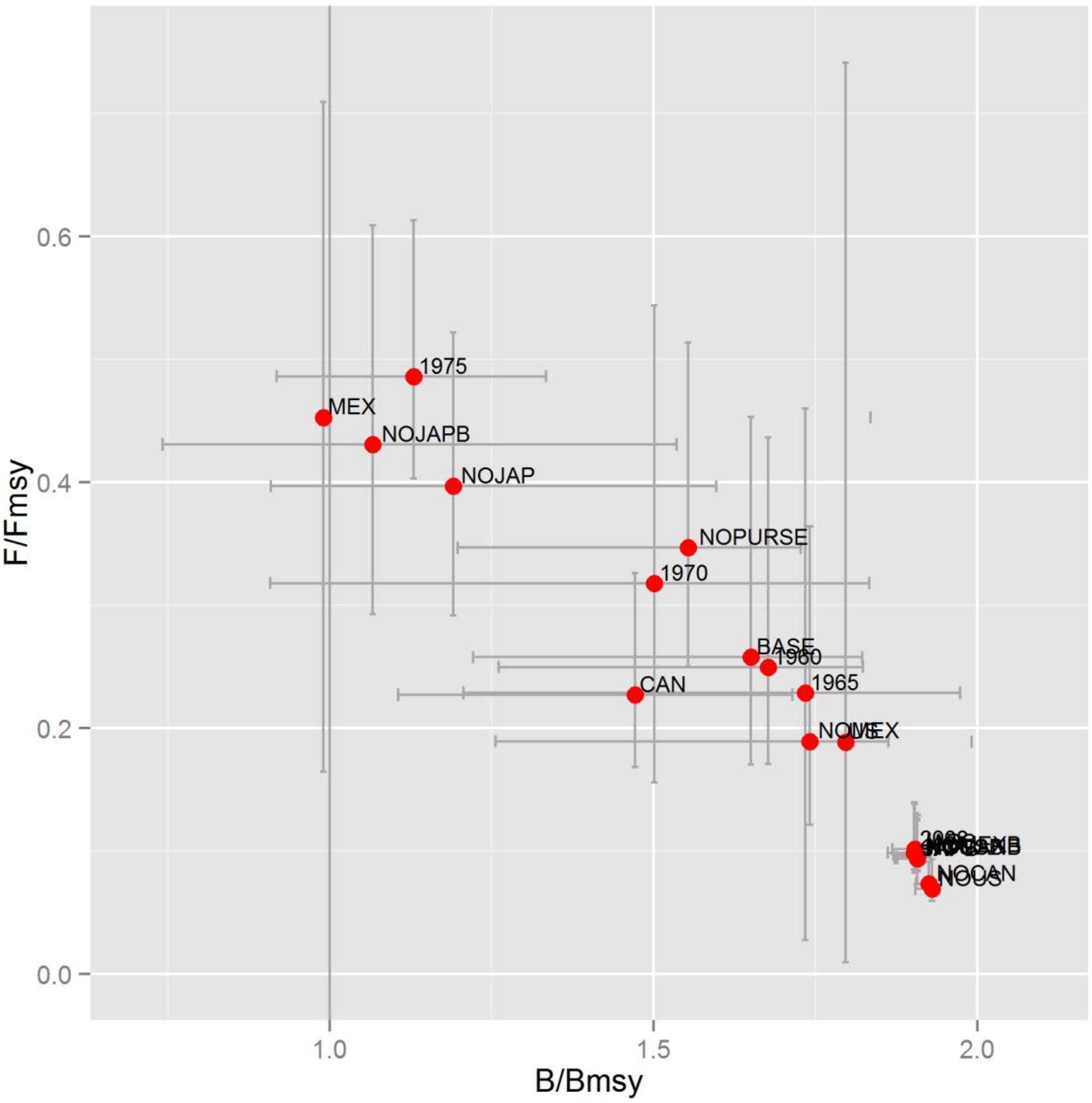

Figure 7. Scatterplot of current relative biomass and relative fishing mortality estimates, with 95% bootstrap confidence intervals, for all scenarios.

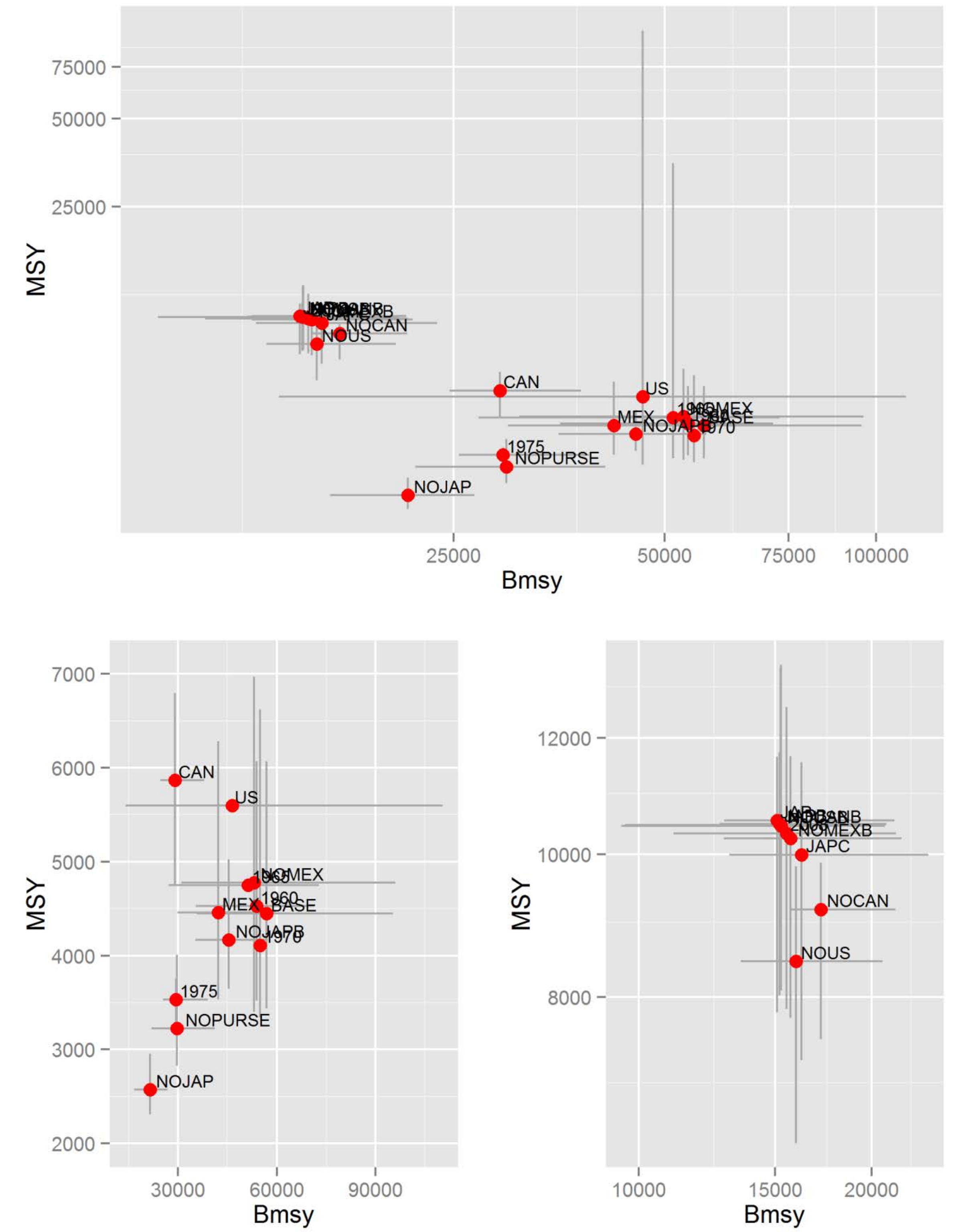

Figure 8. MSY versus B_{MSY} estimates with 95% bootstrap confidence intervals for all scenarios (top). The bottom left and right plots provide expanded views of the top plot.

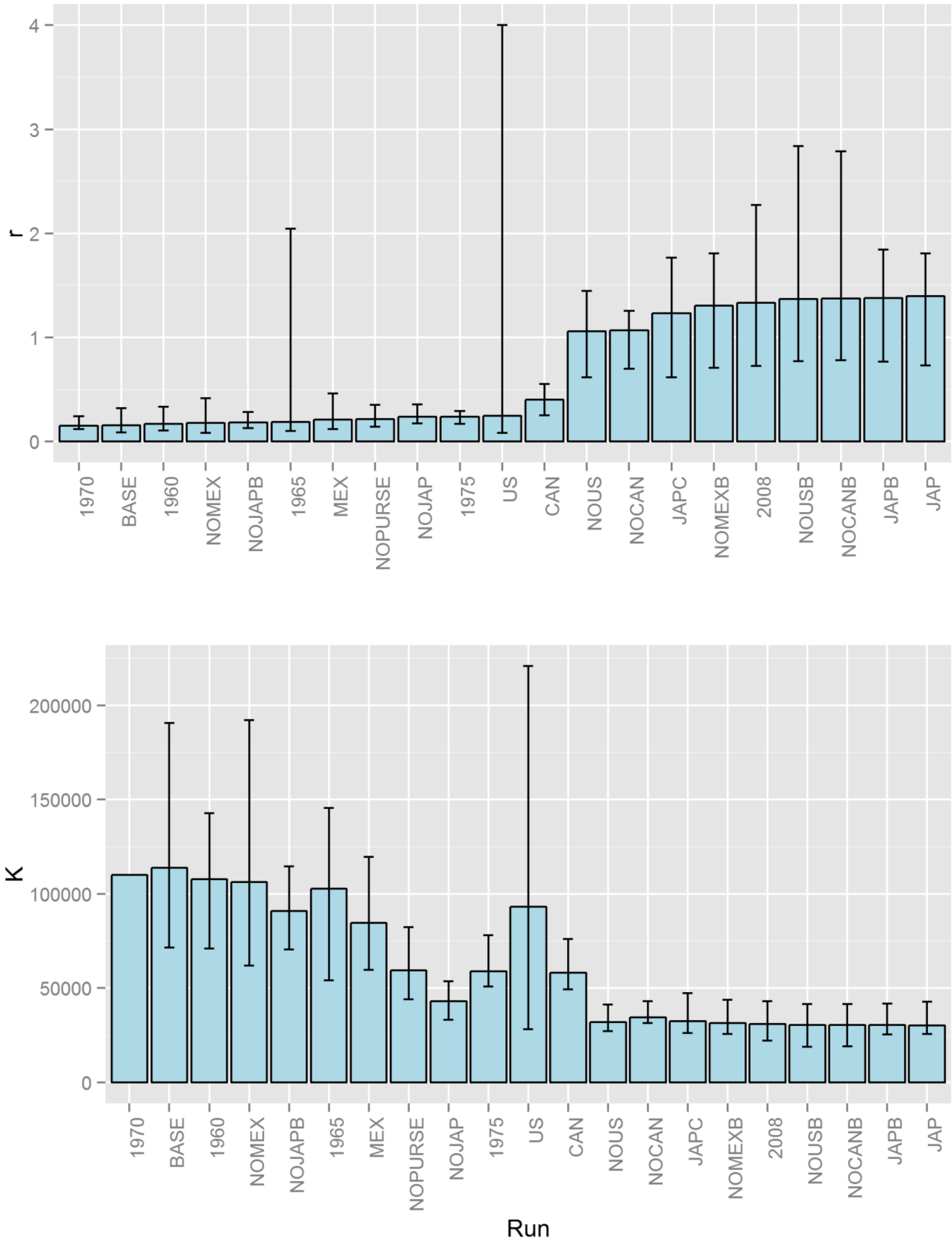

Figure 9. Estimates of the intrinsic rate of population growth (r) and carrying capacity (K) for all scenarios ordered according to increasing values of r. 95% bootstrap confidence intervals are given.

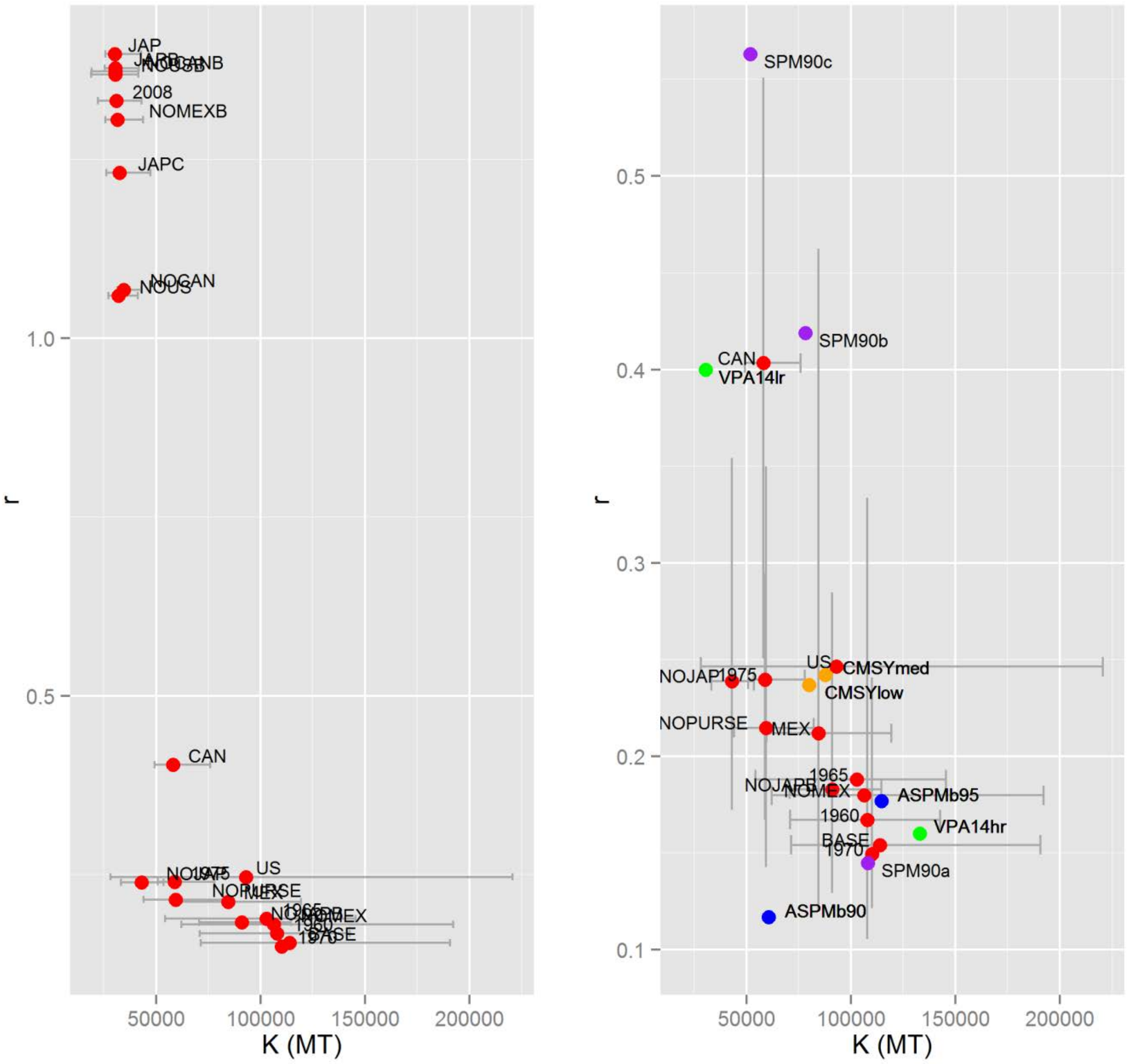

Figure 10. Scatterplot of intrinsic rate of population growth (r) and carrying capacity (K) estimates with 95% bootstrap confidence intervals. The right plot is an enlarged view of the plot on the left with the addition of estimates from (Prager & Scott, 1993) {SPM90a, SPM90b, SPM90c}, (Butterworth & Punt, 1992) {ASPMb90}, (Germount & Butterworth, 1999) {ASPMb95}, (Martell & Froese, 2012){CMSYlow, CMSYmed} and (Lauretta, Kimoto, Porch, & Hanke, 2014) {VPA14hr, VPA14lr}.