Australian Government
Department of the Environment
Australian Antarctic Division

An integrated stock assessment for the Heard Island and McDonald Islands Patagonian toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2

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Based on WG-FSA 17/19

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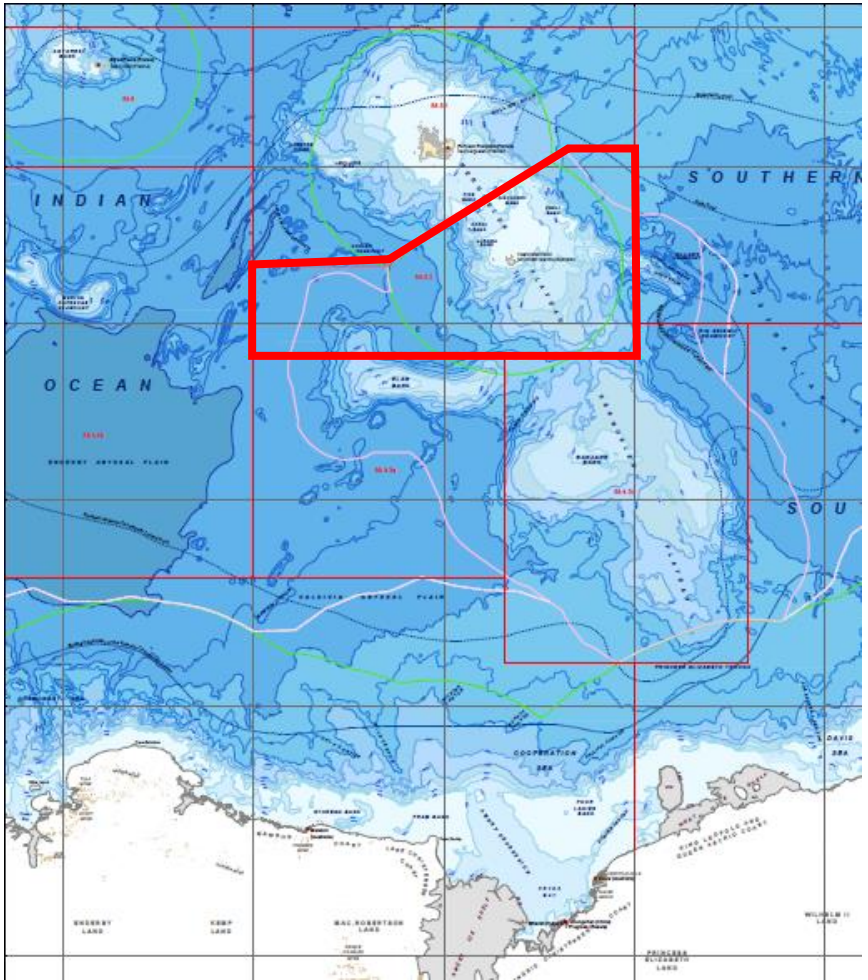
1. Introduction: The fishery in Division 58.5.2

- Target species: Patagonian toothfish (*Dissostichus eleginoides*)
- Division 58.5.2: Domestic fishery on Kerguelen Plateau in Australian Exclusive Economic Zone (EEZ) around Heard Island and McDonald Islands (HIMI) but managed consistent with CCAMLR conservation measures
- Adjacent to Patagonian toothfish fishery in French EEZ (Division 58.5.1)
- Predominantly longline fishery with 4 vessels (one is dual trawl/longline)
- 100% observer coverage, fishery participates actively in data collection
- Comprehensive management arrangements to avoid overfishing, mitigate fish & seabird bycatch
- MSC accreditation & Monterrey Bay Aquarium recommendation
- Also a trawl fishery for mackerel icefish (*Champsocephalus gunnari*)



2. Stock hypothesis

Patagonian toothfish found across the entire Kerguelen Plateau in Divisions 58.5.1 and 58.5.2

- ***Ontogenetic movement*:**

  Péron et al (2016) Modelling spatial distribution of Patagonian toothfish through life-stages and sex and its implications for the fishery on the Kerguelen Plateau. Progress in Oceanography 141 SuppC: 81-95

- ***Movement rates:***

  Burch et al (2017) Estimation and correction of migration-related bias in the tag-based stock assessment of Patagonian toothfish in Division 58.5.2. WG-SAM-17/11

- ***Spawning and settlement areas*:**

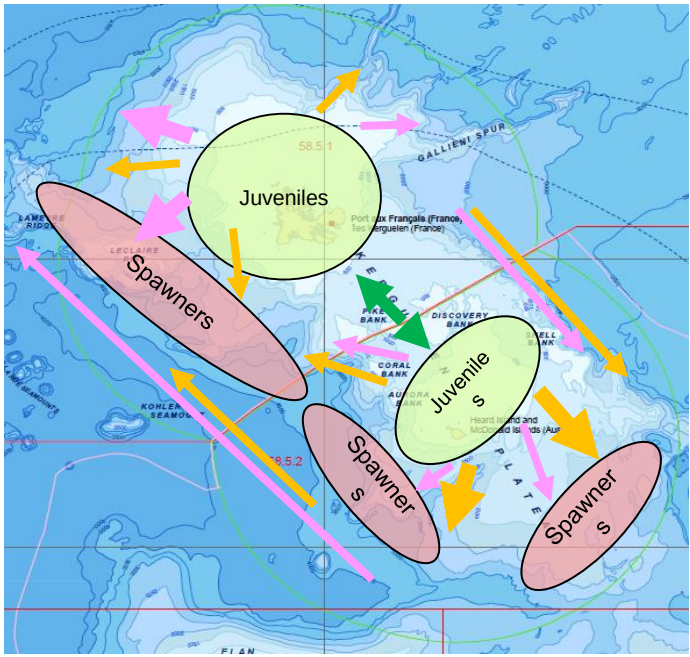
  Welsford et al (2012) The spawning dynamics of Patagonian toothfish in the Australian EEZ at Heard Island and the McDonald Island and their importance to spawning activity across the Kerguelen Plateau. FRDC Report, No 2010/064

  Yates et al (2018) Spatio-temporal dynamics in maturation and spawning of Patagonian toothfish Dissostichus eleginoides on the subantarctic Kerguelen Plateau. Journal of Fish Biology, 92:34-54

  Mori et al (2016) Using satellite altimetry to inform hypotheses of transport of early life stage of Patagonian toothfish on the Kerguelen Plateau. Ecological Modelling 340: 45-56

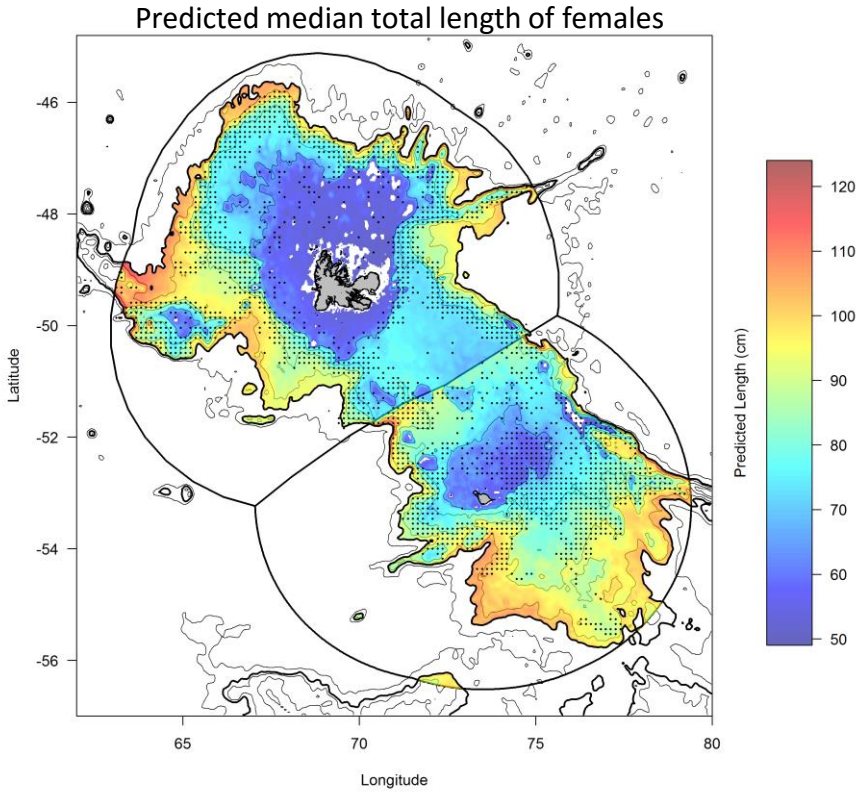
- ***Genetic linkages*:**

  Toomey et al (2016) Genetic structure of Patagonian toothfish populations from otolith DNA. Antarctic Science 2016:1-14



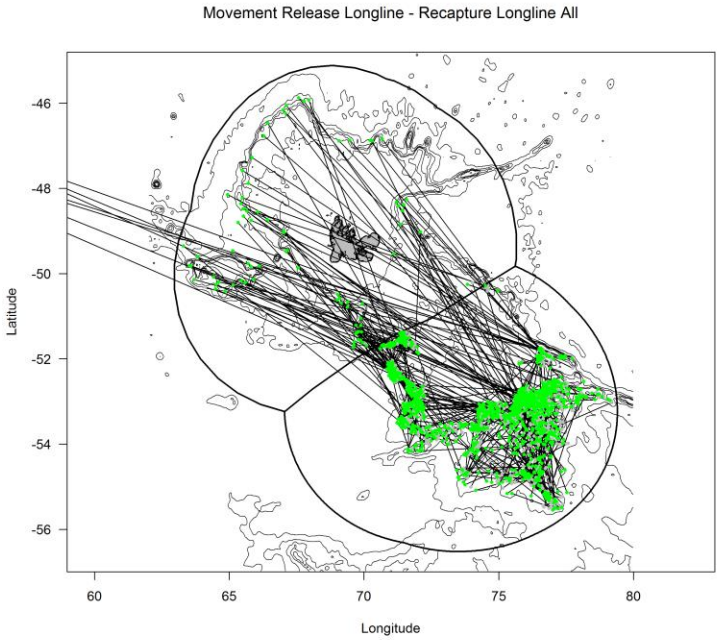
2. Stock hypothesis: Movement

Ontogenetic movement



Gradual migration from shallow to deep waters as fish grow

Directional movement

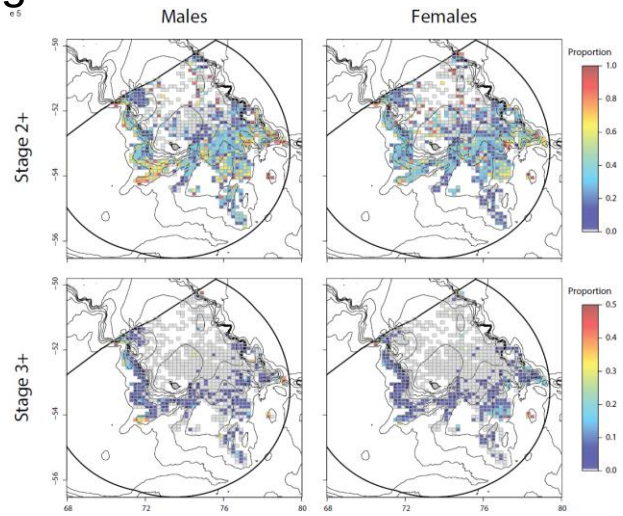


Mostly short distances, but some long distances (including to Crozet Island)

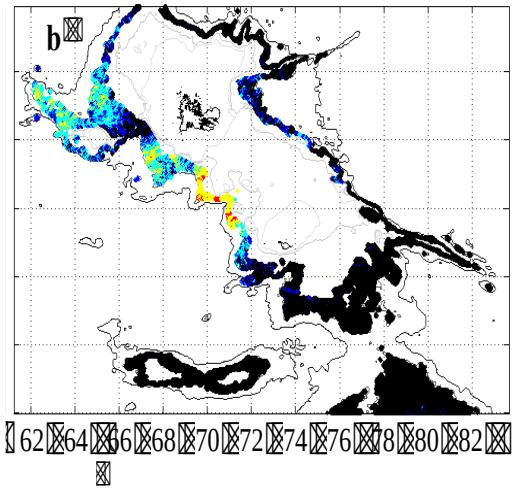
2. Stock hypothesis: Spawning areas & Genetics

Spawning areas

Maturation



Key spawning locations with consistent recruitment success (using AVISO velocity fields 2000-2006)



Spawning areas in both Divisions (west and south), western areas more successful

Genetic linkages

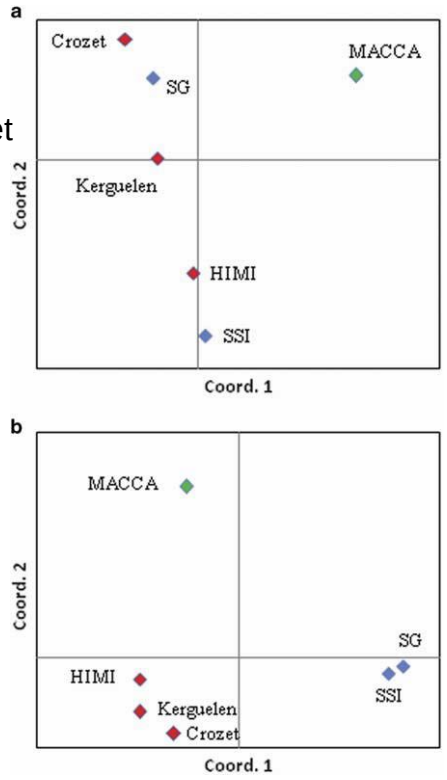
General genetic homogeneity between :

- HIMI and Kerguelen
- Kerguelen and Crozet

Differentiation by mitochondrial but not nuclear markers between:

- HIMI and Crozet

Low level of movement, mainly males?

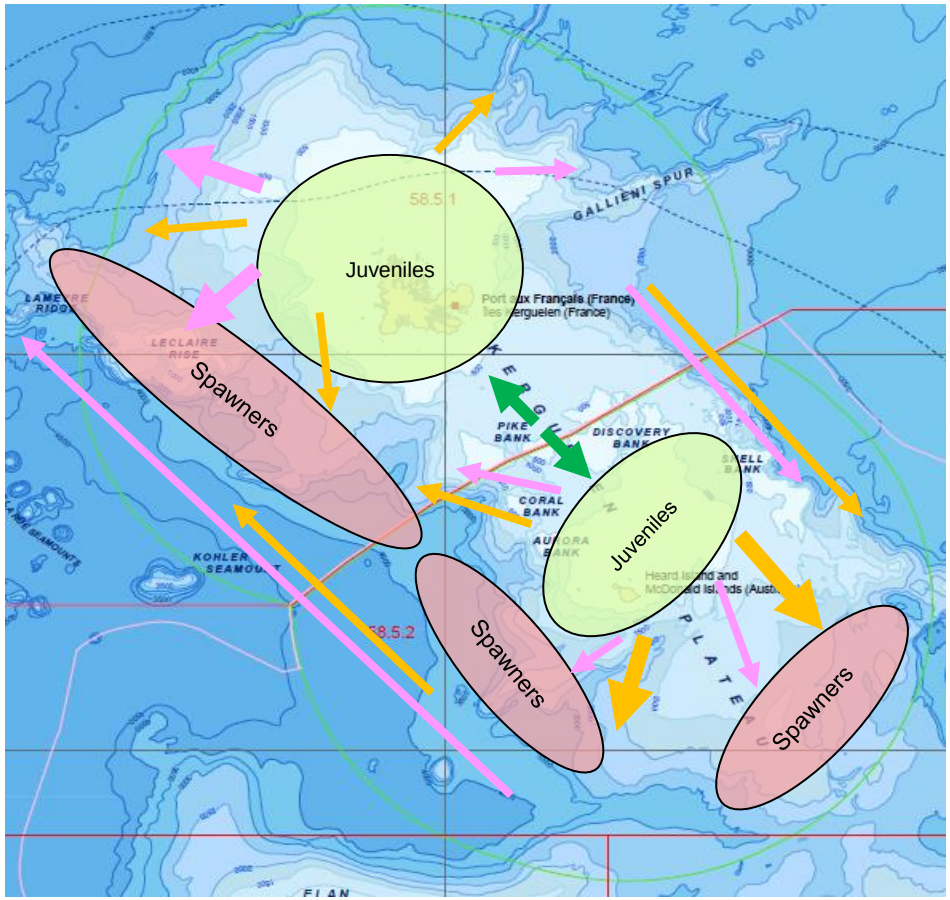


PCA results for a) mitochondrial markers and b) nuclear markers

Stock linkages across Kerguelen Plateau and with Crozet Island

2. Stock hypothesis - Summary

- Settlement and juveniles in shallow habitat, adults in deeper water
- Spawning on western & southern side of Kerguelen Plateau
- Some level of stock linkages across the Plateau (between Australian & French EEZs and Crozet Island)



2. Stock hypothesis: Consequences for stock assessment

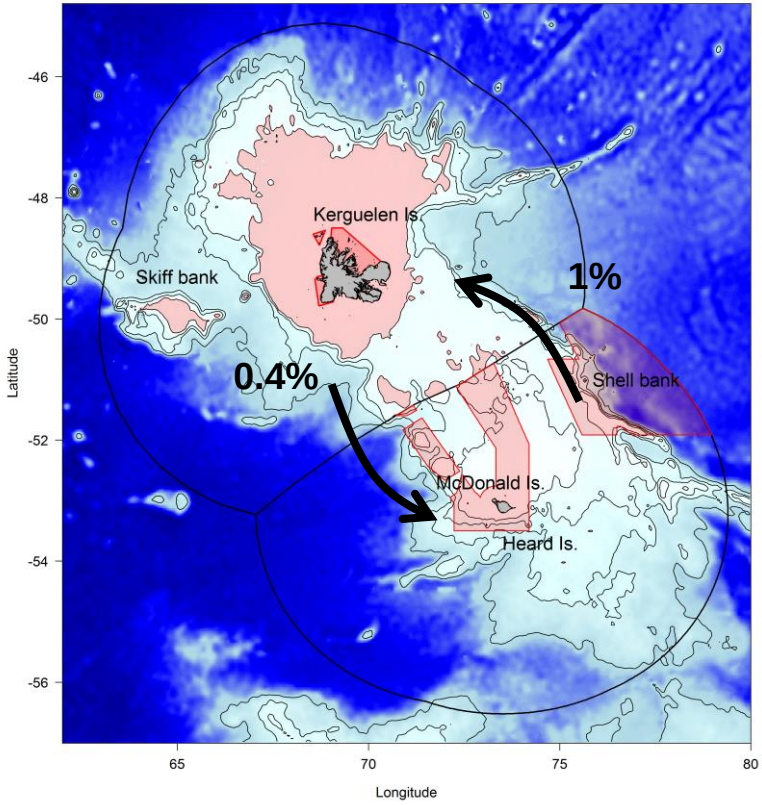
Plateau-wide assessment: Candy et al. 2011 (WG-SAM-11/20)

Assessment results consistent with those from combined assessments

But difficult assessment (non-overlapping fisheries, complex structure, different management arrangements…)

Continued division-based fish assessments: Approach to account for linkages in the respective assessments

- Burch et al. (WG-SAM-17/11) estimated movement rates between Divisions based on longline tag-recaptures:
  58.5.2 recaptures: 1003 (50 in 58.5.1)
  58.5.1 recaptures: 3697 (29 in 58.5.2)
- Movement estimates included in 2017 stock assessments as part of tag-loss parameter (WG-FSA-17/19)



3. Fishing history

Early 1970s Unregulated trawling by Soviet vessels for mackerel icefish

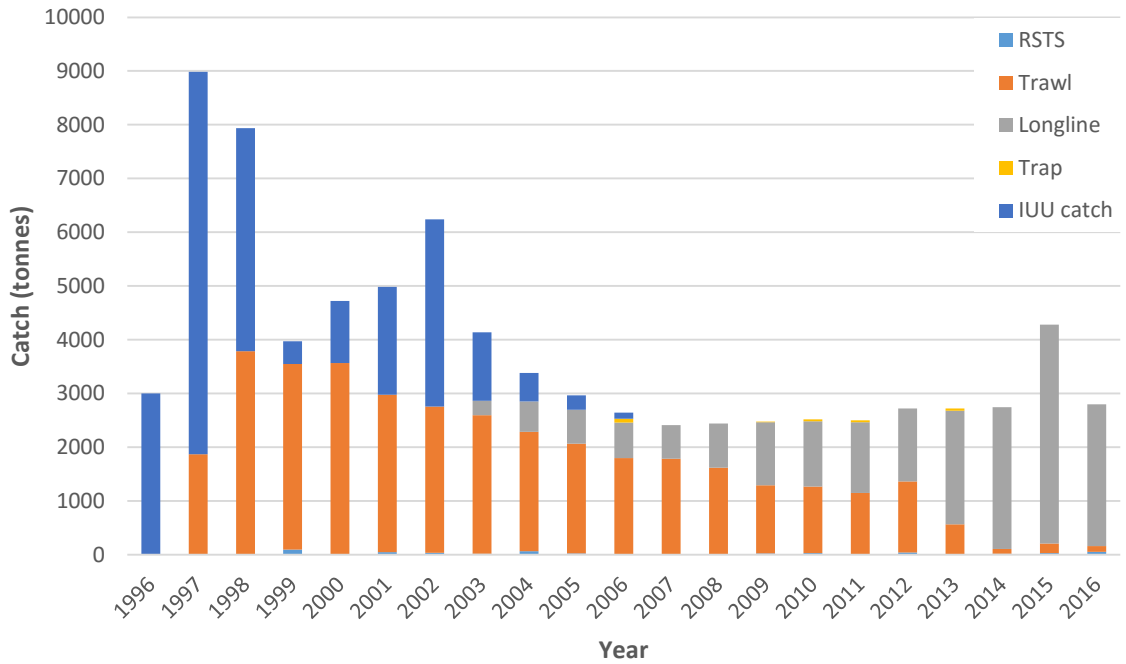
1990-1993 Random stratified trawl surveys (RSTS) to assess potential for commercial fishery

1997 Start of trawl

2003 Start of longline, now dominant method

Trap trials in 2006, 2009-2011, 2013

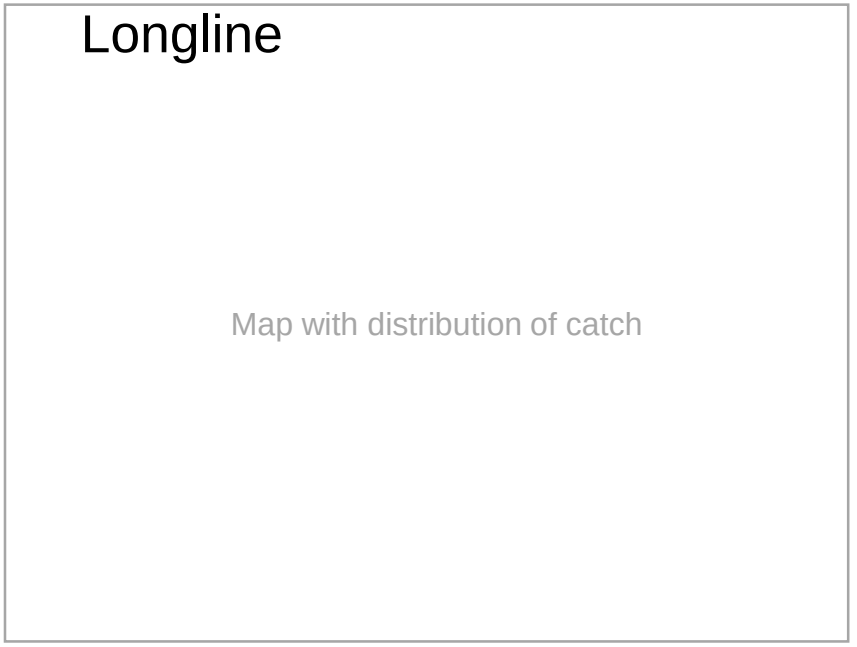
IUU catches in early years (estimated)



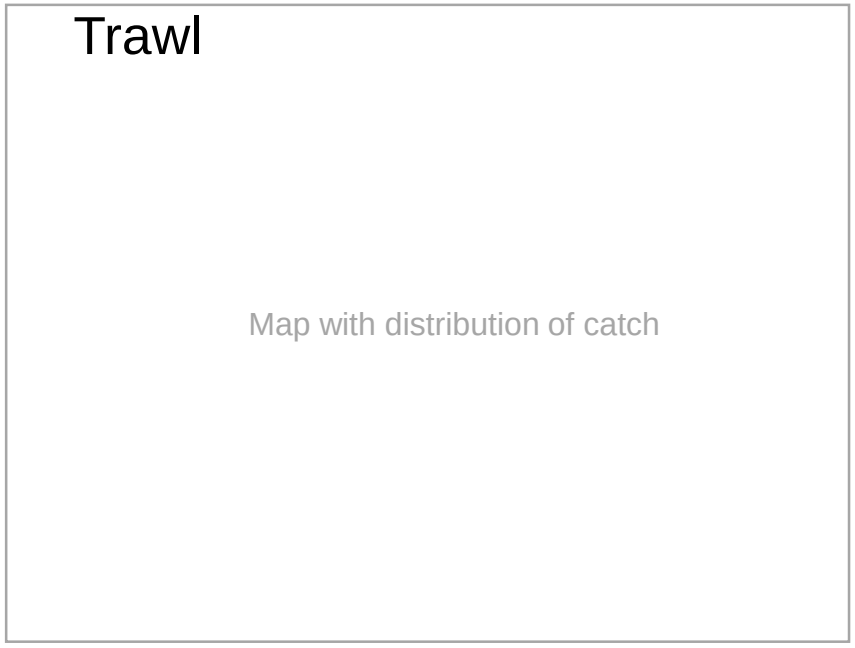
3. Fishing history – Trawl, longline and trap

Survey

Longline

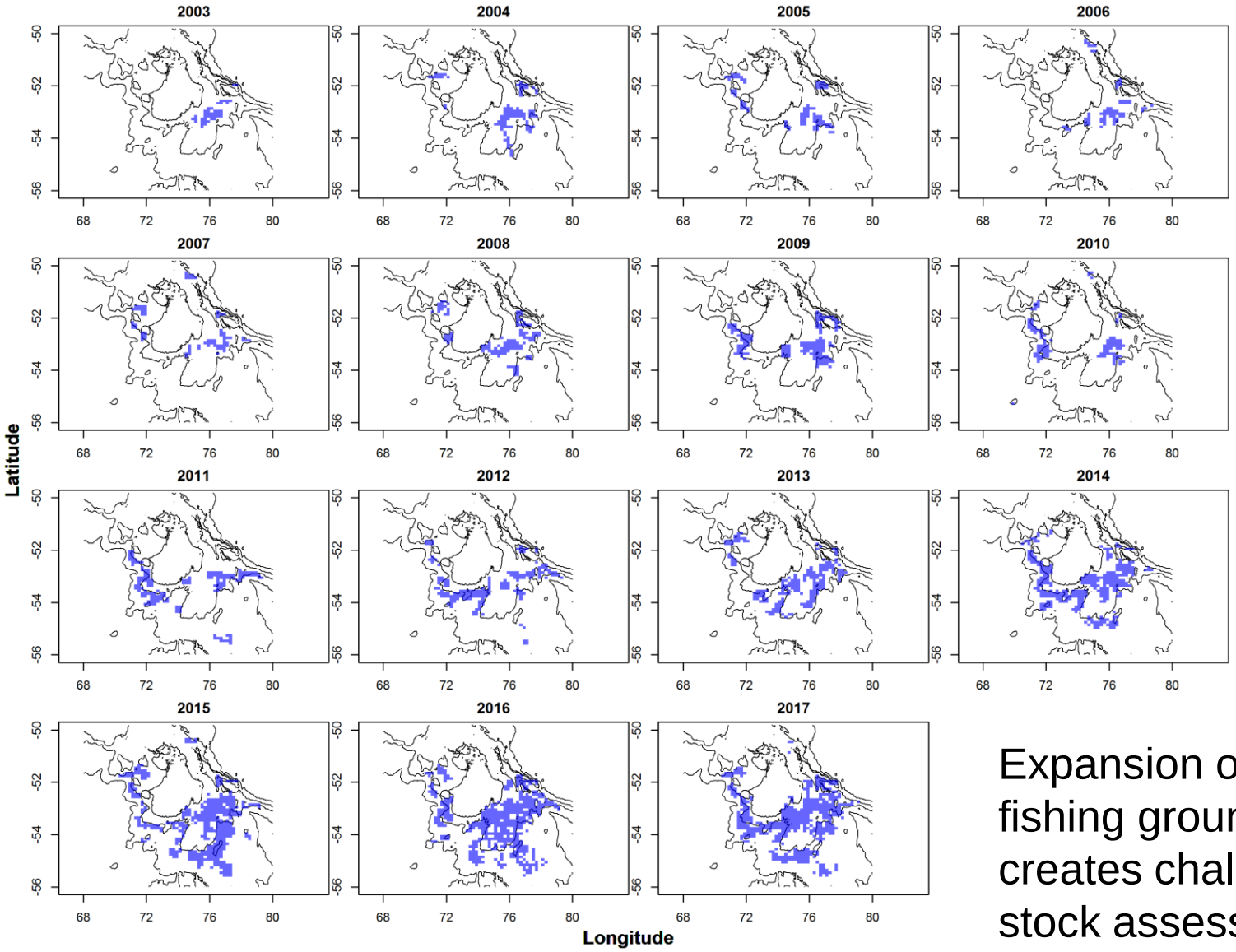


Trawl



Trap

3. Fishing history: Longline



Expansion of longline fishing grounds creates challenges for stock assessment

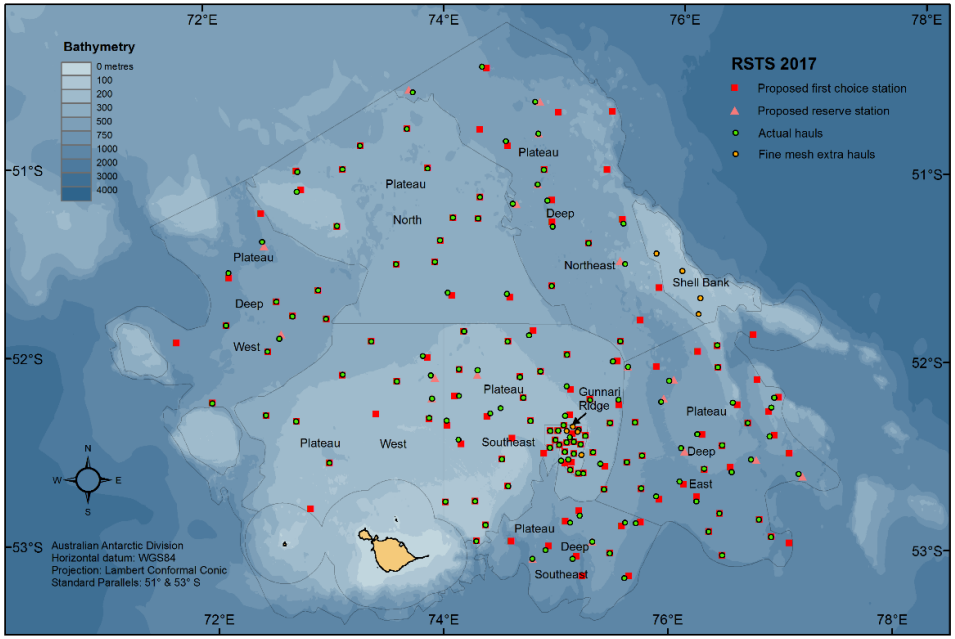
4. Data collection

Data collection:

- Vessel-reported catch and effort
- 100% observer coverage (e.g. biological samples, bycatch composition, benthic samples) – extensive observer training & quality control of data
- Ageing program (~18,000 otoliths aged, double-reads, well-developed protocol)
- Annual random stratified trawl survey (RSTS) since 1999
- Tagging program (>50,000 tagged fish released)

Information for:

- Estimation of biological parameters
- Fish stock assessments
- Impact assessment of fishery on benthic habitat



5. History of stock assessments

Years	Model	Index of abundance	Main changes
1996	GYM	RSTS	Parameters from South Georgia
1999	GYM	RSTS	Estimated growth, maturity, selectivity
2000-2005	GYM	RSTS	Revised parameters
2006-2008	CASAL	RSTS, evaluation to include tag-recapture data from main trawl ground	Model fitted to length composition data, separation of trawl and longline data
2009	CASAL	RSTS	Estimation of ALK & ageing error – age composition data
2011, 2013	CASAL	RSTS	Estimated natural mortality
2014	CASAL	Tag-recapture data from longline	Inclusion of 2 years of tag-recapture data, estimation of survey q
2015	CASAL	Tag-recapture data from longline	Revised parameters
2017	CASAL	Tag-recapture data from longline	Re-estimated maturity, accounting for stock linkages across KP

Since 1996: Regular stock assessments with RSTS as an important input for biomass and year-class estimation:

2006: Move from the population simulation model (GYM) to integrated stock assessment model (CASAL)

2014: Move from the RSTS to tag-recapture data as the main index of abundance

Continued work on estimation of biological and model-related parameters, e.g. growth, maturity, natural mortality, ageing / age-length keys, ageing error, definition of fisheries

6. Data for stock assessment: Sub-fishery structure

See Ziegler (2017, WG-FSA-17/19), in particular Table 6 for summary of data

Definition of sub-fishery: Based on Candy et al. (2013)

GAMM to catch-at-length distribution for single or grouped hauls with cubic smoothing splines for a combination of covariates (e.g. gear type, depth strata and region)

Catches by sub-fishery:

Trawl1: 1997-2004

Trawl2: 2005-2016* (started to target smaller fish)

LL1: <1500m, 2003-2016*

LL2: >1500m, 2004-2016* (GAMM)

Trap: 2006, 2009-2011, 2013 (large fish)

Survey: 2001-2002, 2004-2016*
(surveys with same design)

* 2017 Assessment did not include catches from the 2016/17 fishing season, see WG-FSA-17 para. 3.20: '*should… include the reported catch data where fishing has been completed, or the anticipated catch for the current season'*

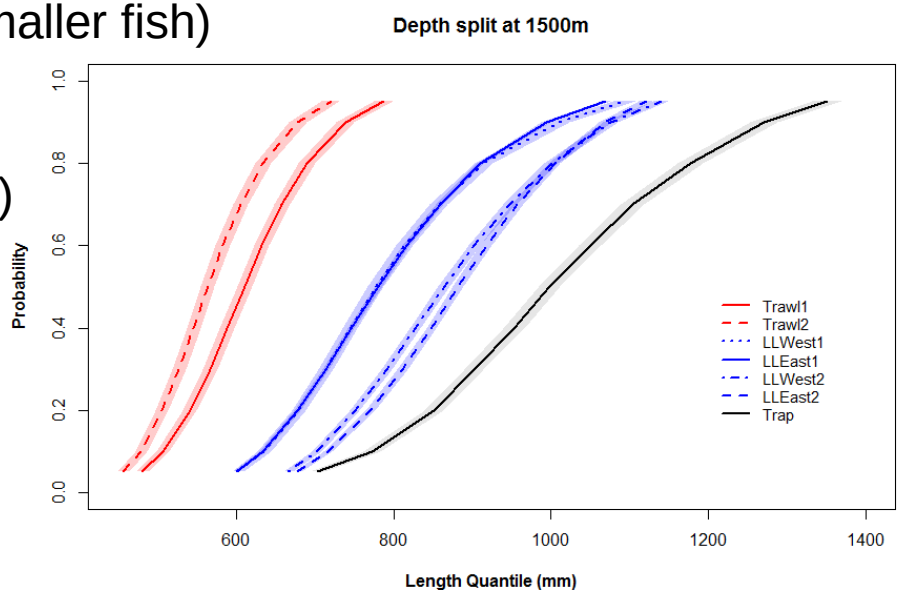


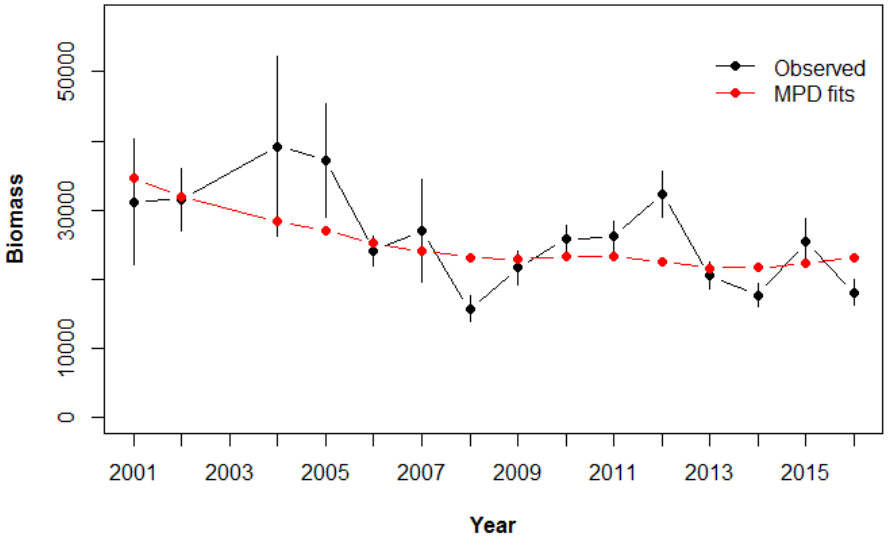
Figure 2: Predicted splines for length quantiles of trawl, trap and longline (LL). Longline hauls were split by fishing areas (west and east of around 74°E), and 1500 m depth, whereas '1' is shallow and '2' is deep. The shaded areas represent the 95% confidence intervals (or two standard errors) of the spline for trawl (red) and trap (black), or of the difference between pairs of splines for longline (blue). The analysis is based on hauls pooled by block size of 1/8° latitude * 1/4° longitude (about 4 * 4 nm).

6. Data for stock assessment: Survey

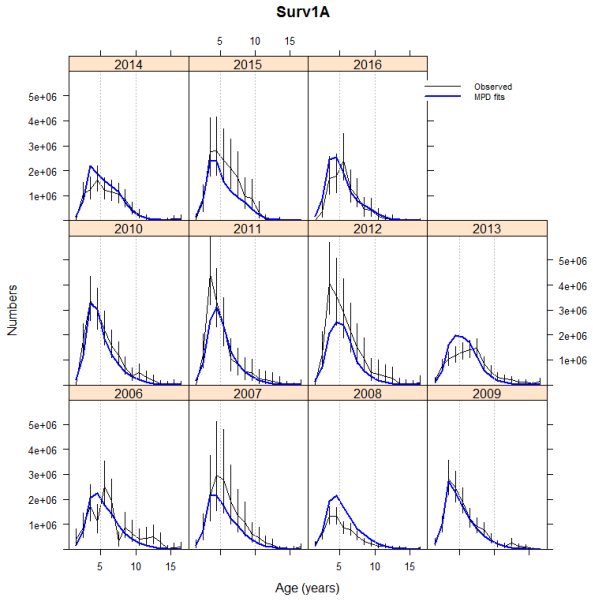
Survey data:

In 2017: Survey abundance-at-age replaced with survey index (stratified bootstrap estimates) and survey catch-at-age

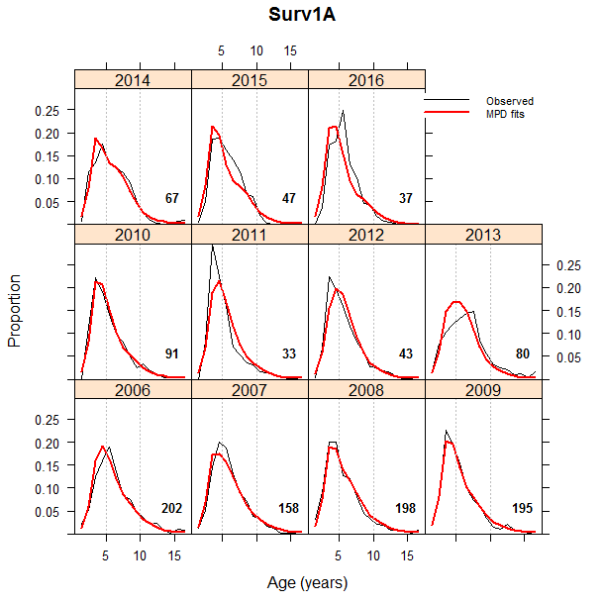
WG-FSA-17, para. 3.21: '*The WG recommended that fitting survey data as two separate datasets, a biomass index and proportions-at-age, is preferred over the numbers of fish at age to be able to distinguish between signals in biomass and year-class strength (YCS) in the survey data*'



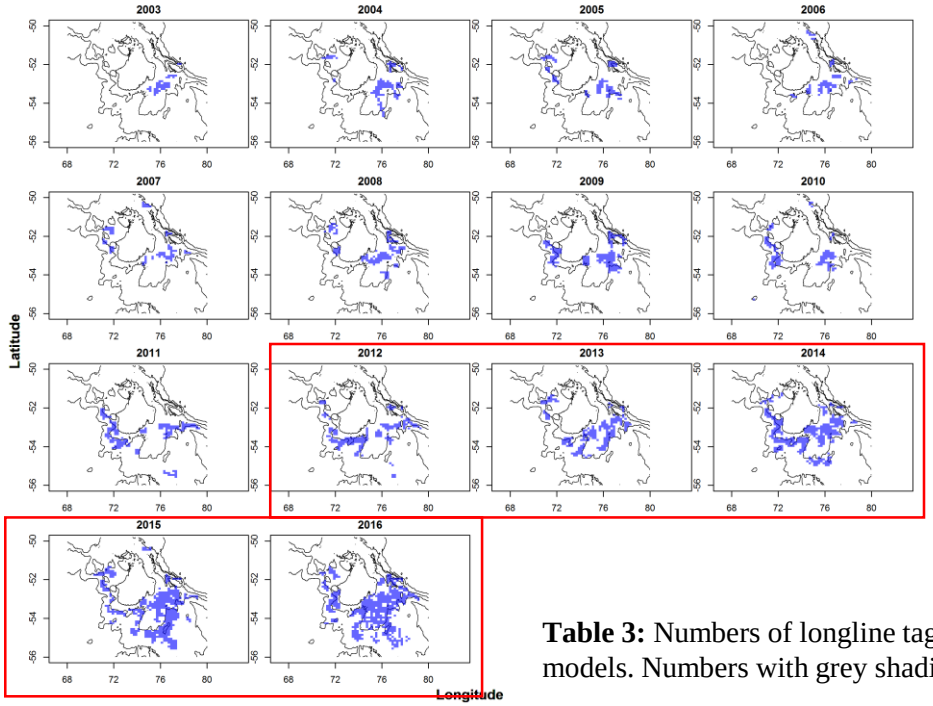
Survey abundance-at-age (Step 5)



Survey index and catch-at-age (Step 6)



6. Data for stock assessment: Tagging data



Releases:
Trawl: 21300
Longline: 31060 (2003-2017)

Longline effort spatially more spread out from 2012 onwards
Inclusion of releases from earlier years explored in sensitivity analyses

Table 3: Numbers of longline tag-releases and tag-recaptures that were used in the assessment models. Numbers with grey shading were only used the sensitivity analyses.

Releases		Recaptures								
Year	Numbers	2009	2010	2011	2012	2013	2014	2015	2016	Total
2008	891	25	14	3	8	23	19	24	9	125
2009	1 242	-	49	44	9	21	39	46	13	221
2010	1 214	-	-	41	5	12	52	36	9	155
2011	1 197	-	-	-	20	19	35	39	27	140
2012	1 433	-	-	-	-	22	40	39	21	122
2013	1 467	-	-	-	-	-	52	94	37	183
2014	1 799	-	-	-	-	-	-	77	58	135
2015	7 631	-	-	-	-	-	-	-	261	261
Total	16 874	25	63	88	42	97	237	355	435	1342

6. Data for stock assessment: Catch-at-age

Catch-at-age by sub-fishery: Estimated from catch-at-length, year-specific age-length keys (ALKs) and ageing error for survey and commercial catches
Effective samples sizes ESS : min(N aged, robust non-linear least squares fit of log(*cj*) ~ log(*Oj*) with multinomial distribution) – Francis 2011

Table 2: Number of toothfish measured for length or age and used in the assessment for the RSTS and commercial fisheries. Where numbers are in bold, the ages have been used to calculate age-length keys (ALKs).

Year	Length			Age		
	RSTS	Commercial	Total	RSTS	Commercial	Total
1997	0	11 387	11 387	0	**55**	55
1998	169	11 229	11 398	0	**286**	286
1999	2294	14 623	16 917	2	**623**	625
2000	2258	20 483	22 741	20	**807**	827
2001	2505	27 079	29 584	2	**909**	911
2002	2965	18 476	21 441	4	**829**	833
2003	2301	27 298	29 599	13	**675**	688
2004	2462	33 509	35 971	4	**336**	340
2005	2355	28 899	31 254	1	**370**	371
2006	2081	31 427	33 508	**119**	**1100**	1219
2007	2050	22 843	24 893	**547**	**588**	1135
2008	1281	31 475	32 756	**652**	**107**	759
2009	1922	44 342	46 264	**642**	**77**	719
2010	5893	30 485	36 378	**918**	**129**	1047
2011	2484	35 568	38 052	**520**	**142**	662
2012	6062	37 026	43 088	**549**	**140**	689
2013	2912	42 736	45 648	**266**	**1249**	1515
2014	2769	50 417	53 186	**571**	**526**	1099
2015	3869	73 739	77 608	**656**	**559**	1215
2016	5630	57 078	62 708	**315**	**537**	852
Total	54 262	650 779	705 041	5801	11533	17 334

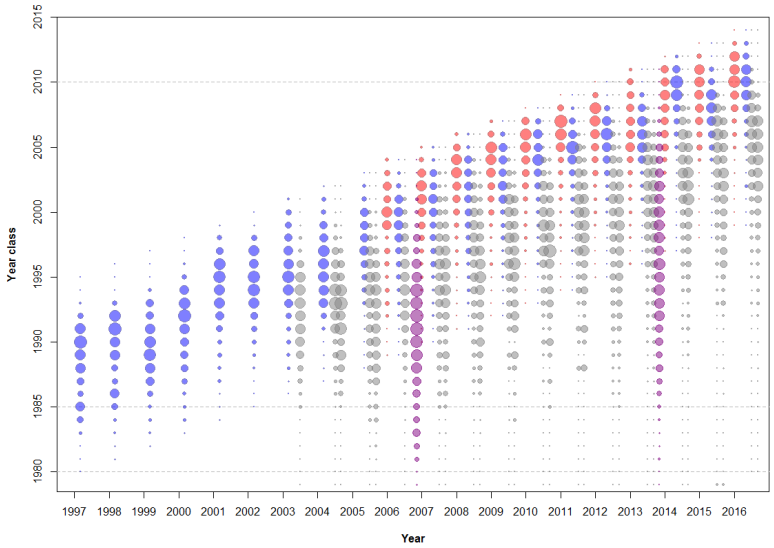


Figure 3: Bubble plot of age observations by year for the survey (red), trawl (Trawl1 and Trawl2, blue), longline (LL1 and LL2, grey) and trap (purple).

6. Data for stock assessment: Input parameters

WG-FSA-17/19, Table 6:

Parameter	Estimate	Source
Stock–recruitment relationship	Beverton-Holt Steepness h = 0.75	WG-SAM-06, para. 2.51
Size-at-age	Von Bertalanffy L_∞ = 2116 K = 0.030 t_0 = -5.31 CV = 0.128	WG-FSA-17/19
Ageing error matrix		Burch et al. (2014)
Weight at length L (mm to t)	c = 2.59E^{-12} d = 3.2064	WG-FSA-99/68
Maturity	Logistic: a_{50} = 13.9 a_{to95} = 13.7	Yates et al. (2017)
Natural mortality	M = 0.155	Candy et al. (2011)
Tagging data		
Tag detection	1	Training & fish handling on board
Tag-release mortality	0.1	Agnew et al. 2006
No-growth period	0.5 y	88.1 Assessment
Tag loss	2012-2015: 0.016	WG-FSA17/21, includes emigration bias correction (0.01)

6. Data for stock assessment: Input parameters

Growth

Model accounts for fishing selectivity function and the effect of length-bin sampling

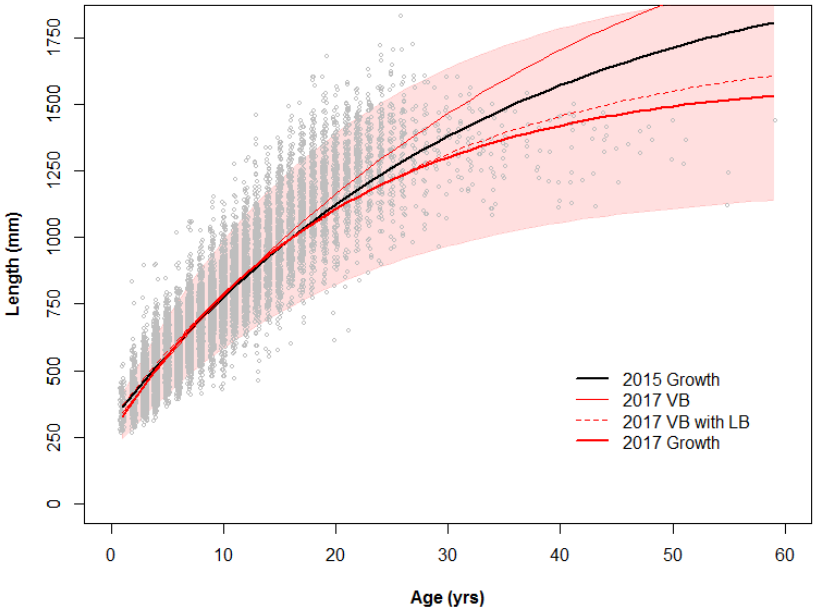


Figure 6: Length-at-age data (grey), growth model used in the 2015 assessment ('2015 Growth', black line), simple von Bertalanffy model ('2017 VB', thin red line), von Bertalanffy model that accounted for length-bin sampling ('2017 VB with LB', red dashed line), and final von Bertalanffy model that accounted for length-bin sampling and dome-shaped selectivity and used in the 2017 assessment ('2017 Growth', bold red line) with approximate 95% confidence intervals of the data based on *CV* (red shade). Sample size $N = 16\,188$.

Maturity

Based on Yates et al. (2017)

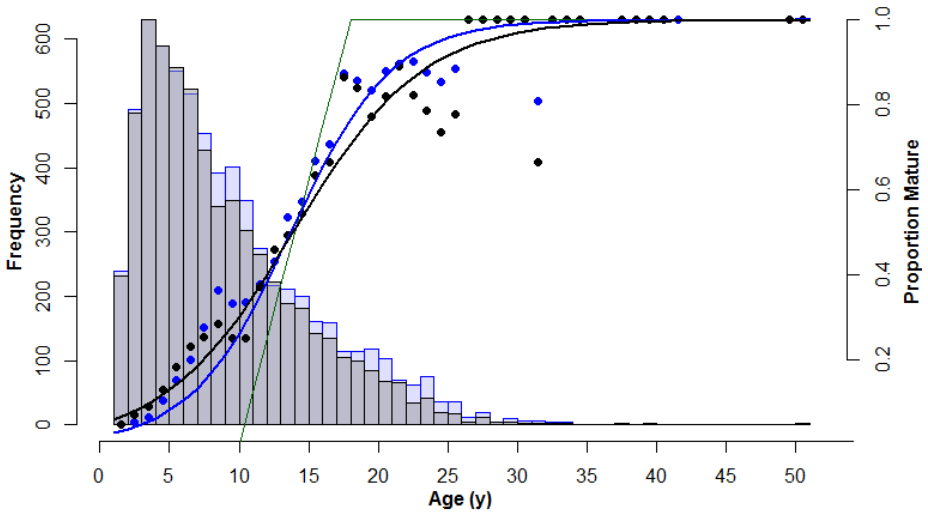


Figure 7: Maturity-at-age used in Models 1 to 2 (green line), and estimated maturity-at-age assuming all fish of stage ≥ 2 are mature (black) and all fish stages ≥ 2 will be mature at their age + 2 years (blue). Shown are age-frequency histograms, proportions of fish that were mature pooled in 1-year age bins (points), and fitted values obtained by logistic regression (lines). Figure adapted from Yates et al. (2017).

7. Model estimation: Model structure & estimated parameters

WG-FSA-17/19, Table 6:

Parameter	Details	Prior, Starting value (bounds)
General	Single-area, single-sex	
Assessment period	1986-2016	
Age classes	1 - 35 y	
Length classes	300 - 2000 mm (50 mm bins)	
Penalties	Mean *YCS* = 1	100
	Catch penalties: Maintain exploitation rate $U < 0.995$	1000
Estimated parameters:		
- B_0	Estimated	Uniform-log, 90k (30k-250k)
- Survey *q*	Estimated	Uniform-log, 1 (0.1-1.5)
-YCS	1986-2011	Lognormal, $\mu = 1$ (0.001-200), $CV = 0.6$
- Fishing selectivities		
Survey, Trawl1, Trawl2	Double normal	Uniform a_1: 4 (1 - 20) σ_L: 1 (0.1 - 20) σ_R: 7 (0.1 - 20)
LL1, LL2, Trap	Double plateau-normal	Uniform a_1: 10 (1 - 20) a_2: 6 (0.1 - 20) σ_L: 1 (0.1 - 20) σ_R: 3 (0.1 - 20) a_{max}: 1 (1 - 1)
Number of estimated parameters	48	

8. Model estimation: Procedure

1. Bridging analysis
Starting with assessment model used to provide management advice in previously and leading step-wise to new proposed assessment model
General sequences:

1. Update data
2. Update estimates of input parameters
3. Update model structure and procedure (if applicable)

2. Model procedure for each model step
- Initial data weighting:
Survey biomass index & CV (lognormal)
Survey age composition with ESS (Francis 2011)
Commercial age composition with ESS (Francis 2011)
Tag-recapture data (2012-2016) by 100mm length bins

- Iterative model fitting following Francis (2011):

1. Reweighting of commercial age composition
2. Reweighting survey age composition
3. Estimate tag dispersion ϕ and account for overdispersion

$$w_j = \frac{1}{\mathrm{var}_i\left[(O_{iy} - E_{iy}) / \sqrt{(v_{iy} / N_{iy})}\right]}$$

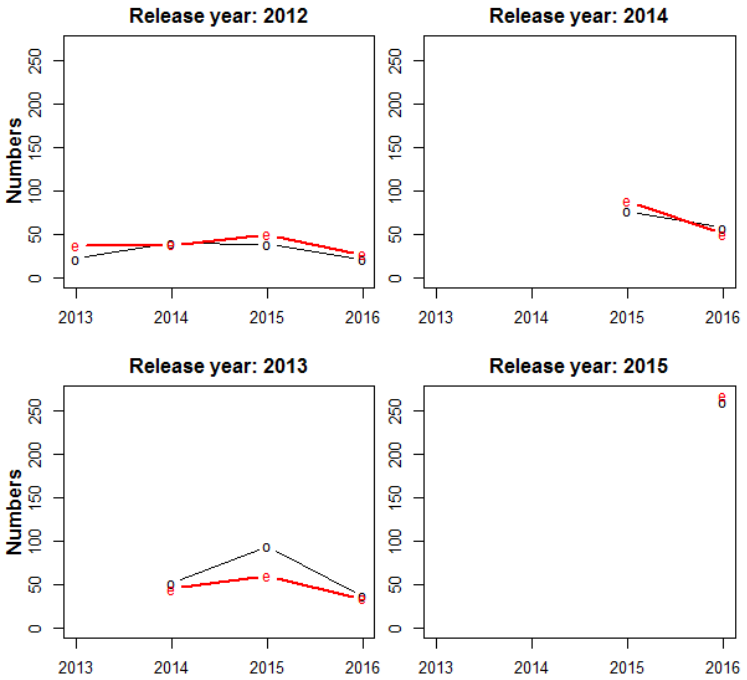
$$\phi_j = \mathrm{var}\left(\frac{O_{ij} - E_{ij}}{\sqrt{E_{ij}}}\right)$$

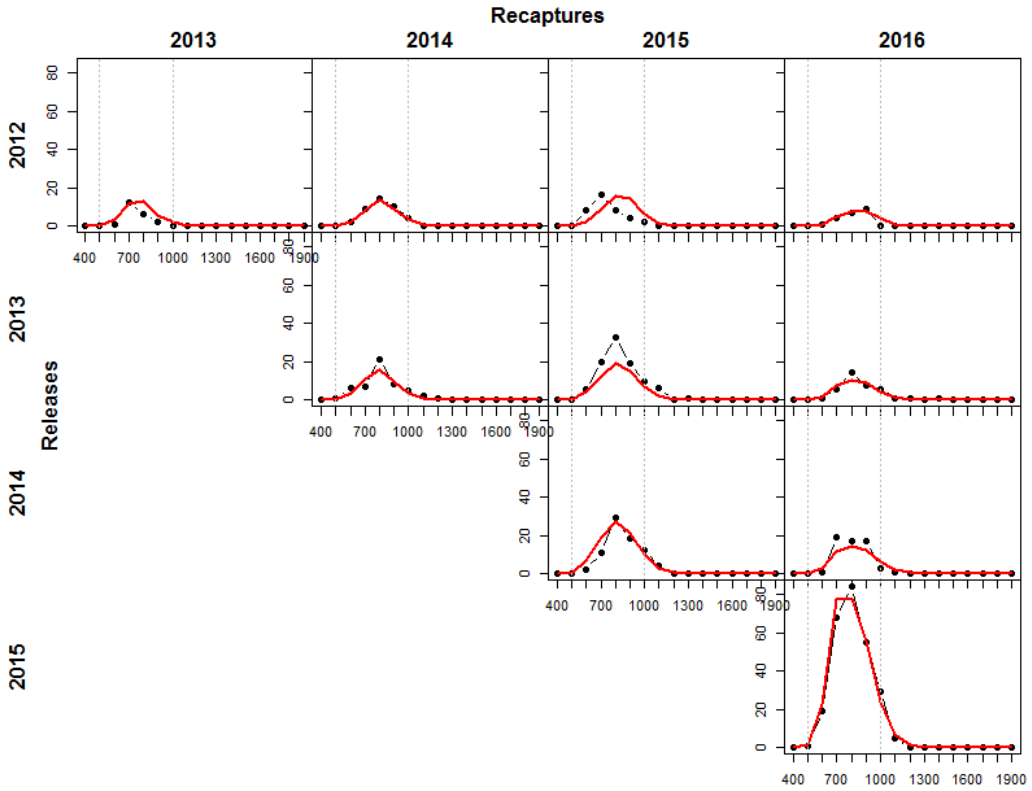
4: Evaluate MPD fits & likelihood profiles, then run MCMC

8. Model estimation: 2017 Bridging analysis

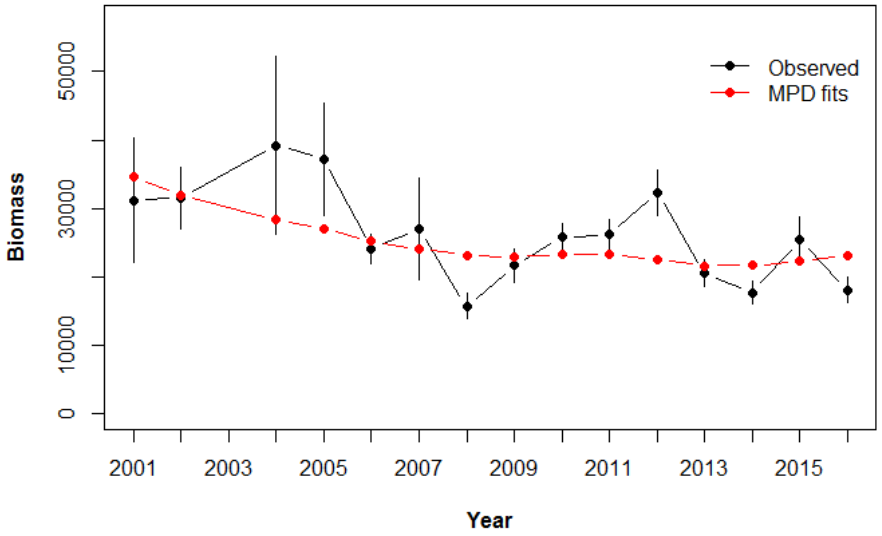
Step	Description	B_0	*SSB* status
0	2015 Assessment model (Ziegler and Welsford 2015)	88 020	0.64
1	Update model to include data until the end of the 2015/16 season	78 673	0.60
2	Update growth parameters	70 447	0.56
3	Update maturity estimates	73 770	0.59
4	Update tag-loss rate estimates	73 611	0.59
5	Include bias correction for fish emigrating out of Division 58.5.2	72 970	0.59
6	Replace survey numbers-at with survey biomass and proportions-at	79 971	0.63
7	Replace iterative data weighting from ‘Candy’ method to ‘Francis’ method	**78 845**	**0.62**

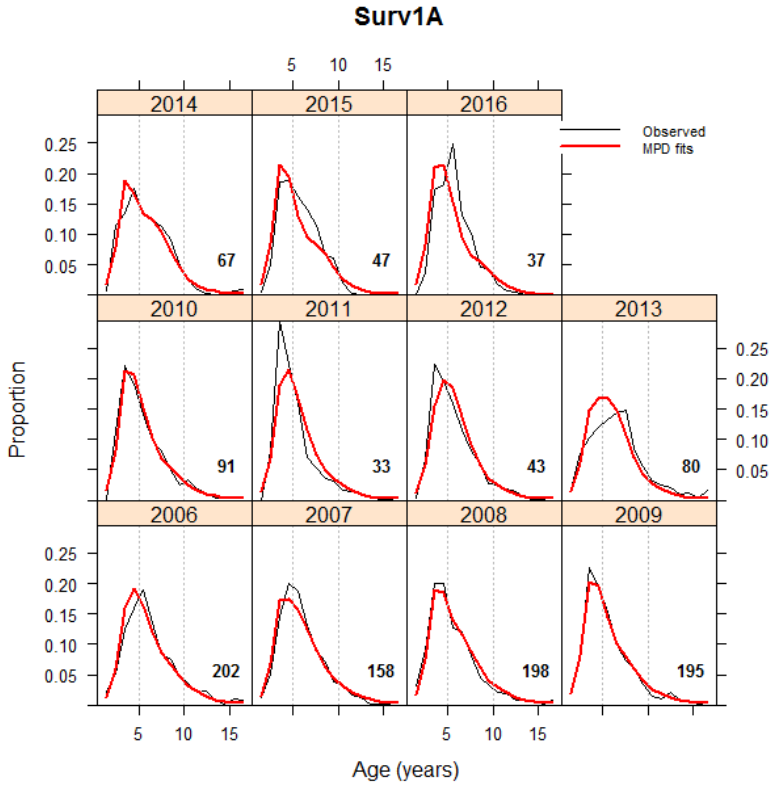
8. MPD fits: Tagging data

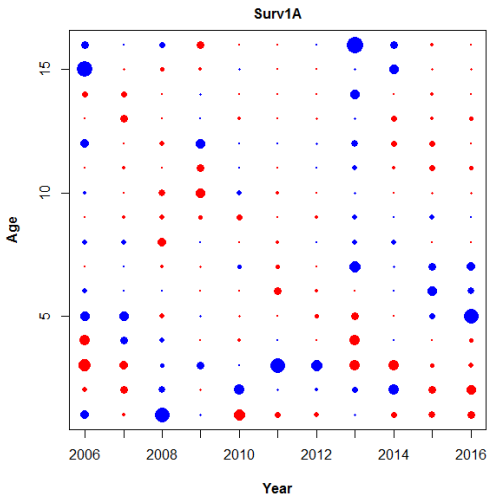




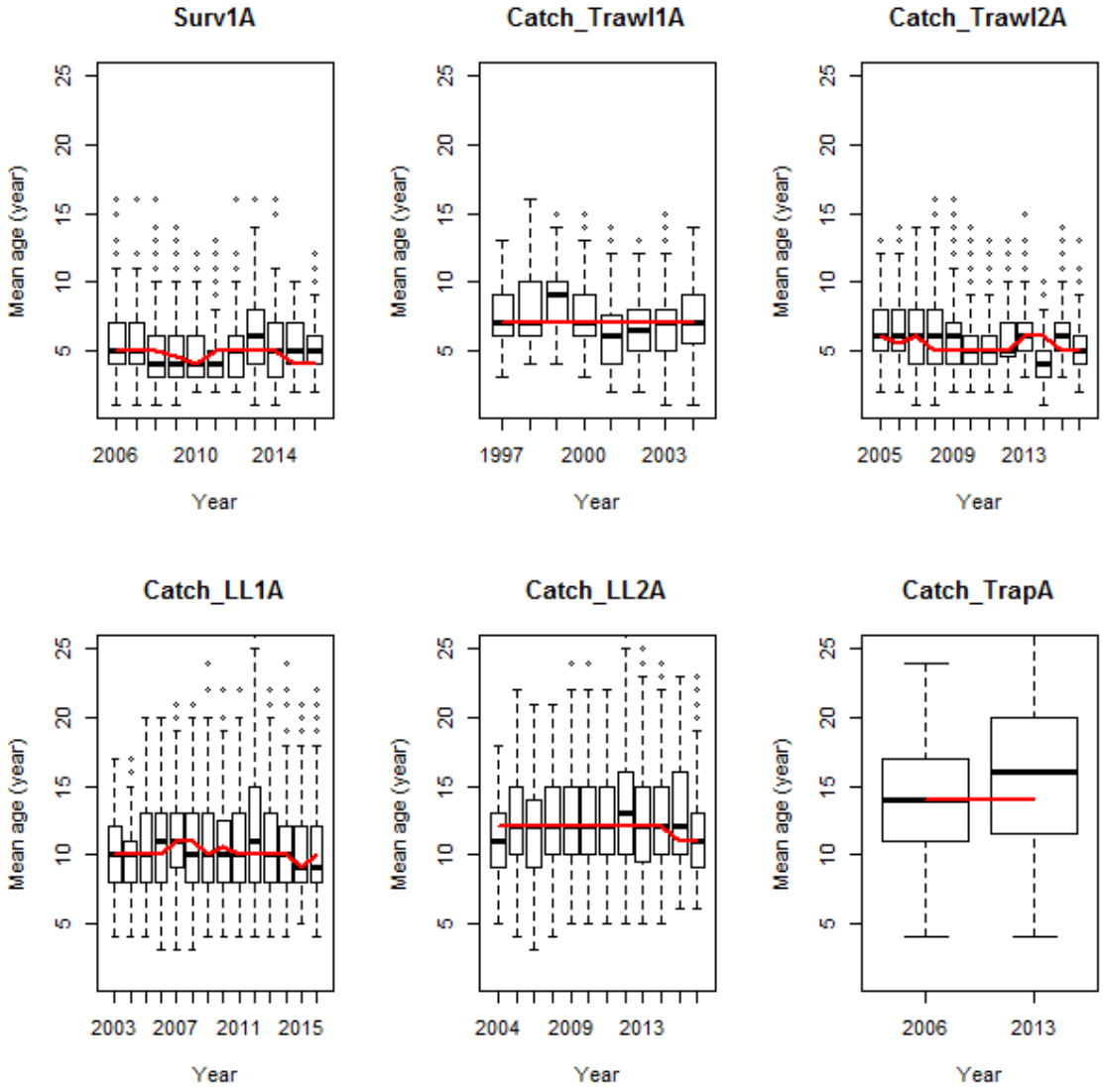
8. MPD fits: Survey data



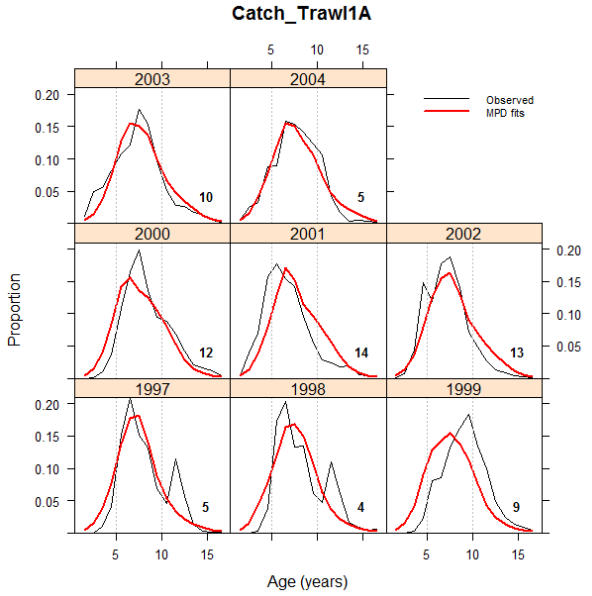


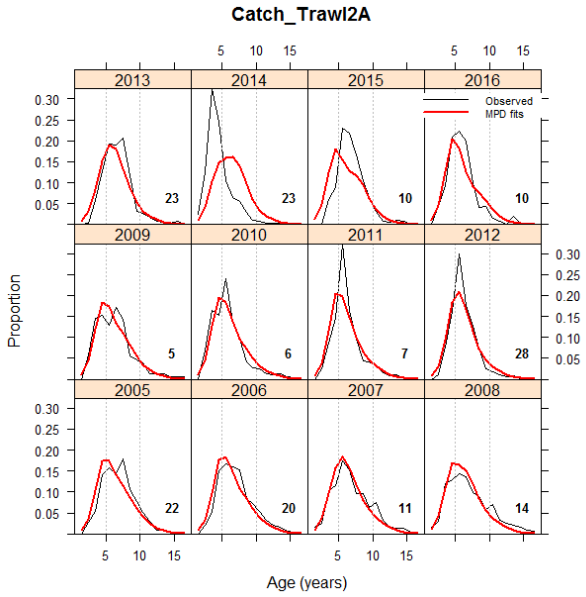


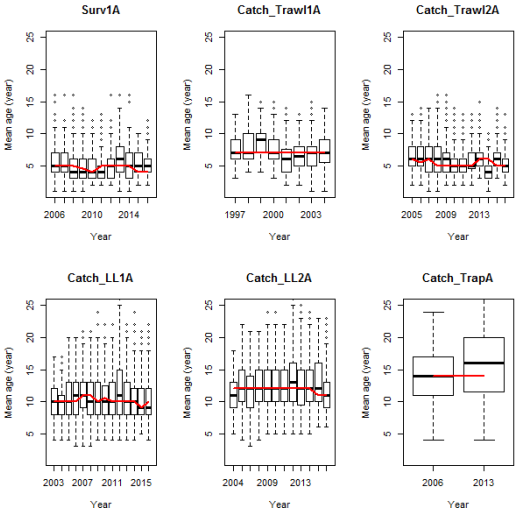
8. MPD fits: Age composition

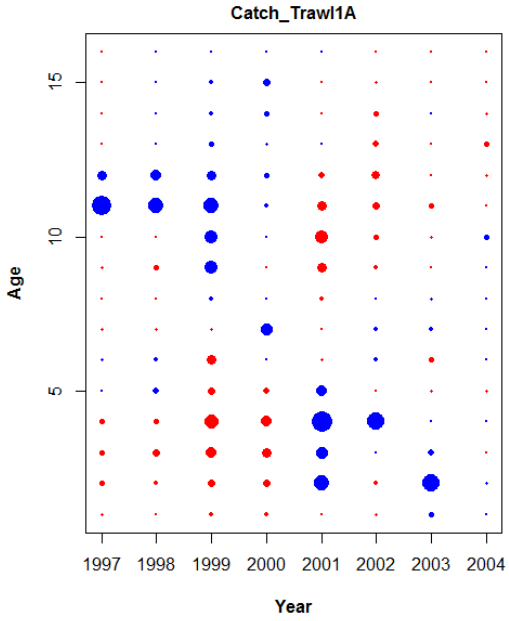


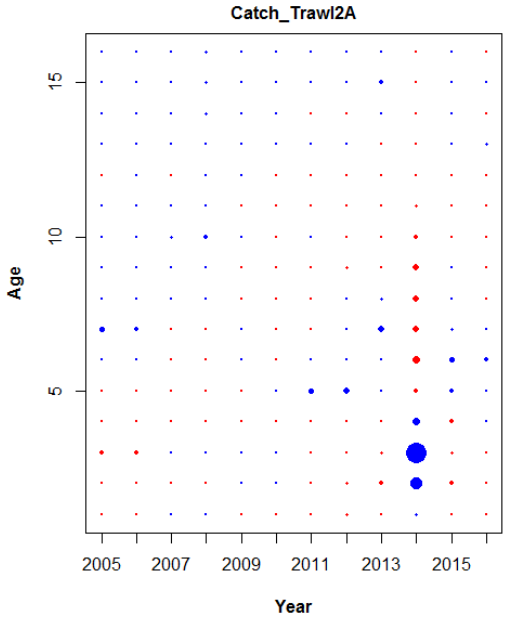
8. MPD fits: Age composition



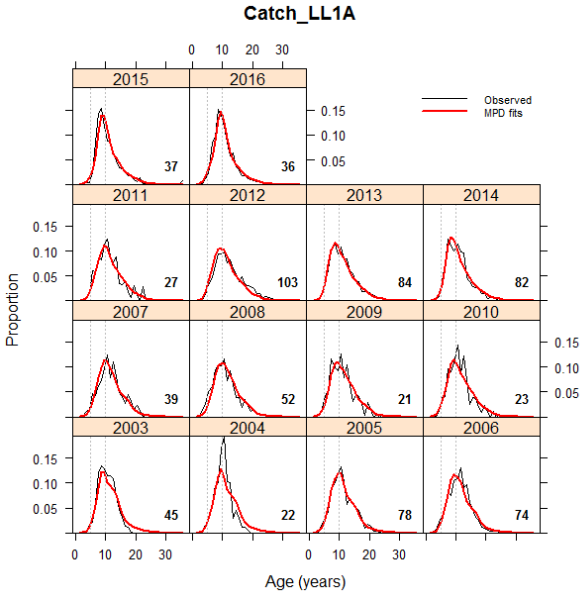


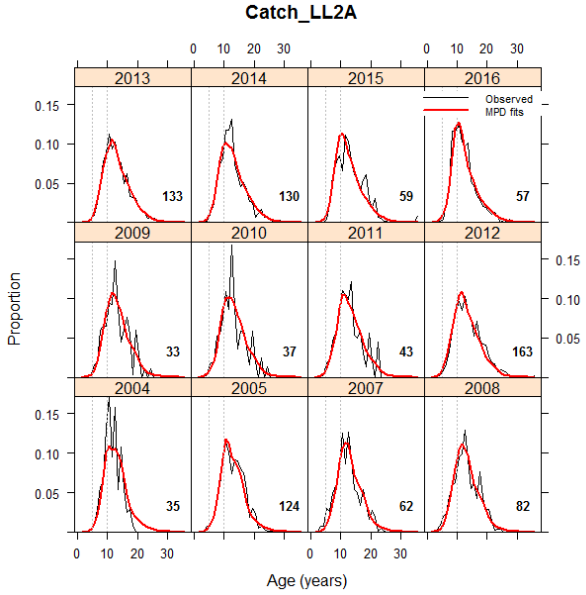


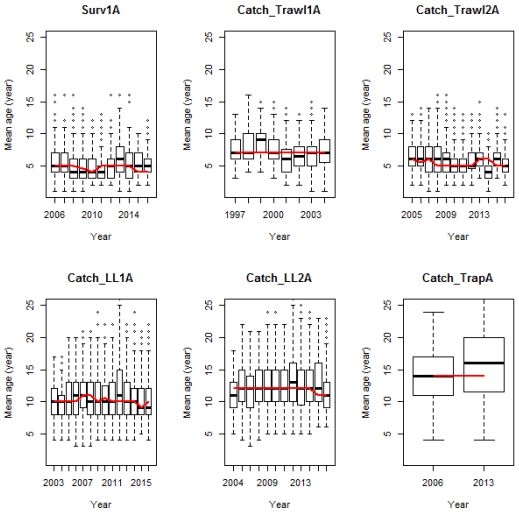


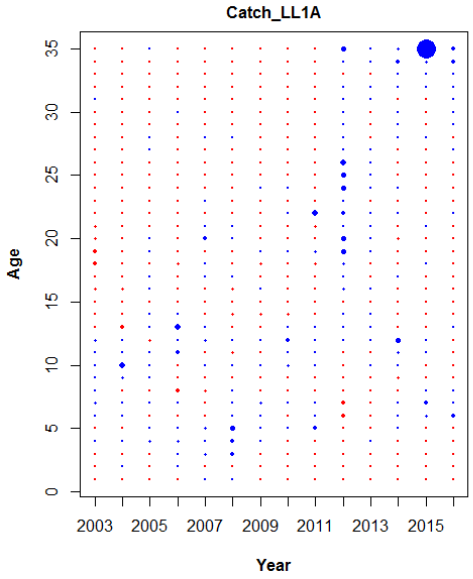


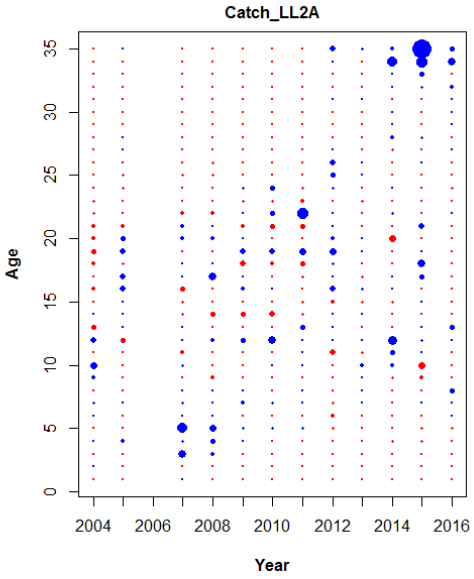
8. MPD fits: Age composition

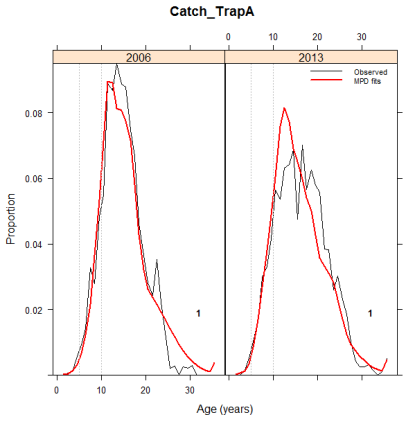






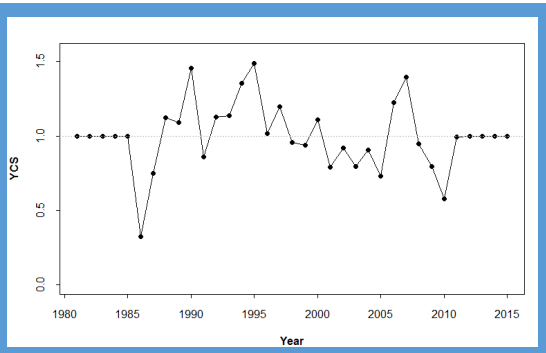




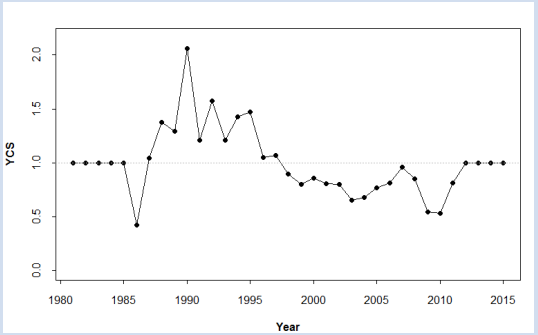


8. MPD fits: YCS estimates

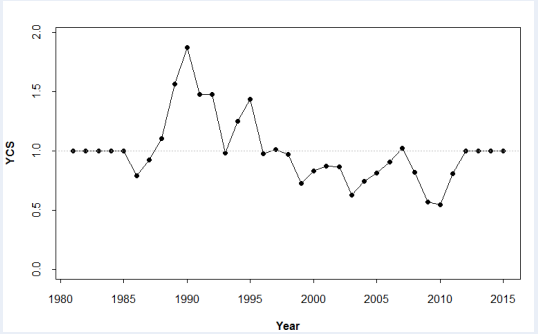
M5



M6



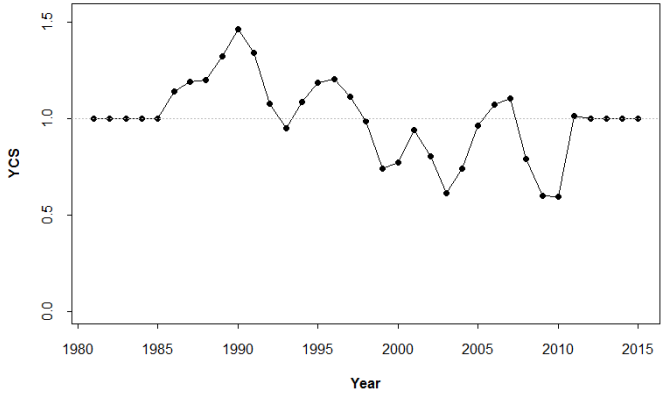
M7



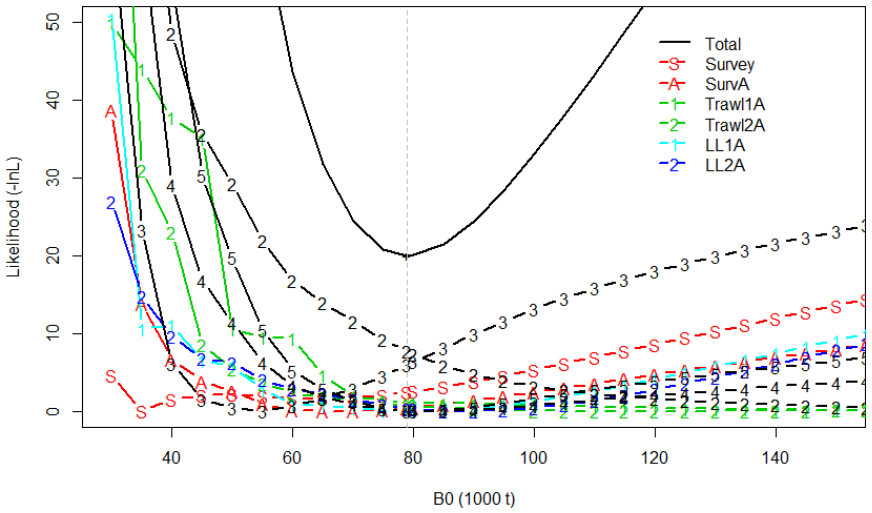
Drivers for YCS trend
Little change with removal or down-weighting of:

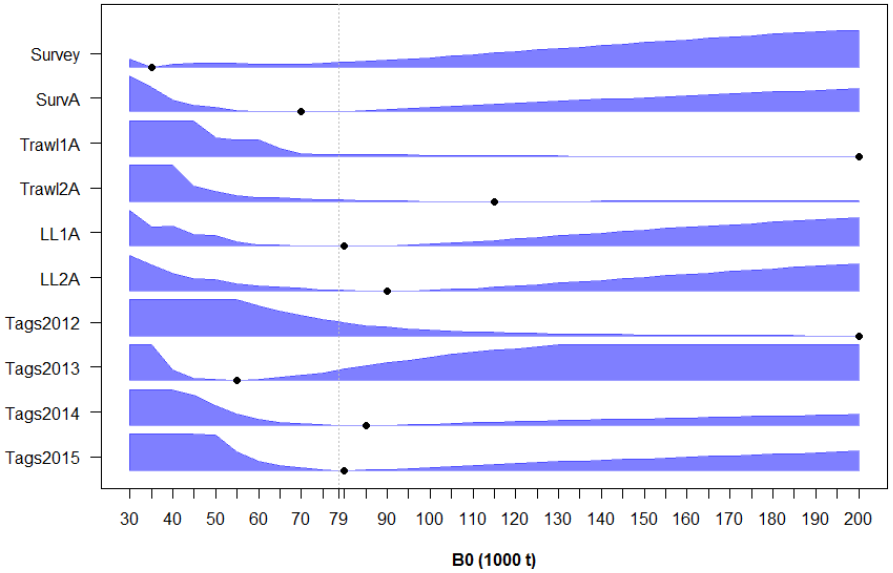
- Survey biomass
- Survey AF
- Trawl AF
- Longline AF
- Tagging data

Down-weighting of Longline AF

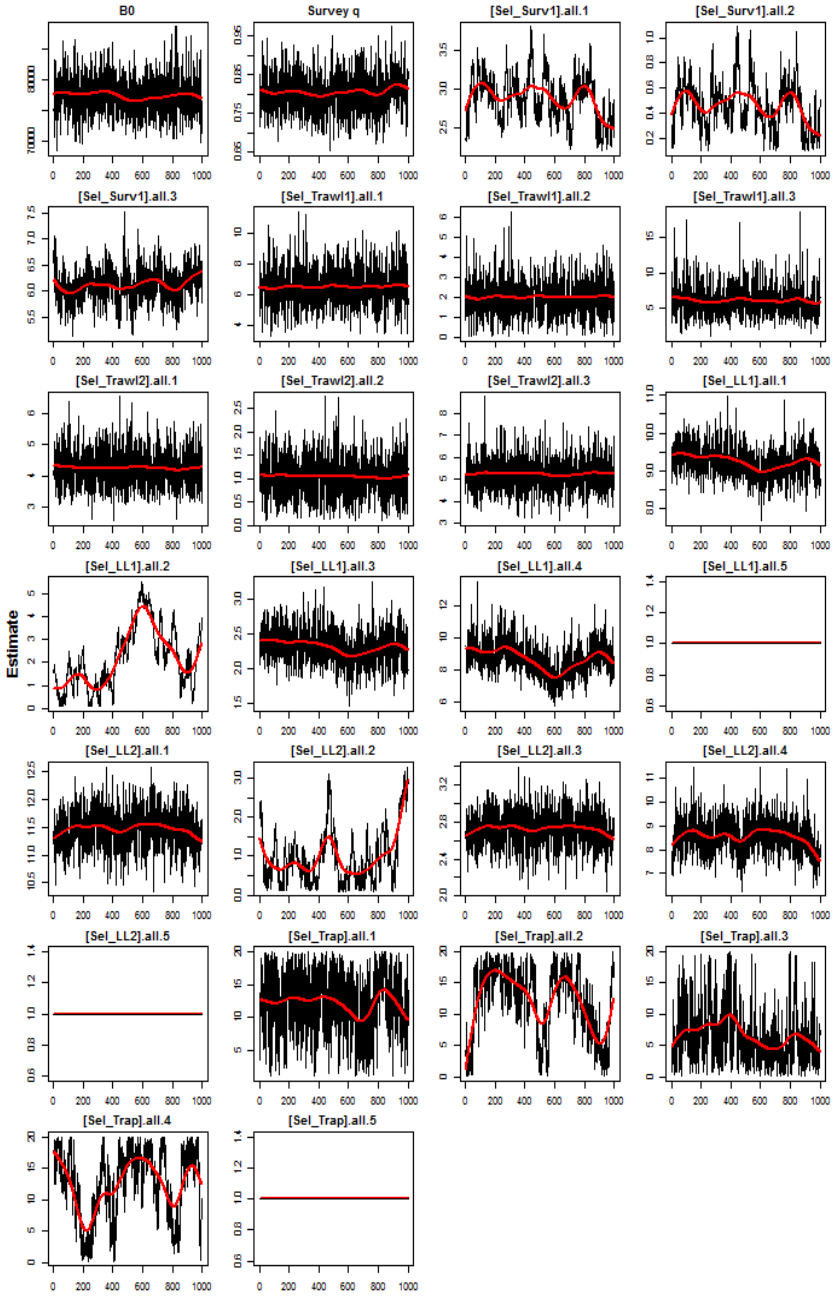


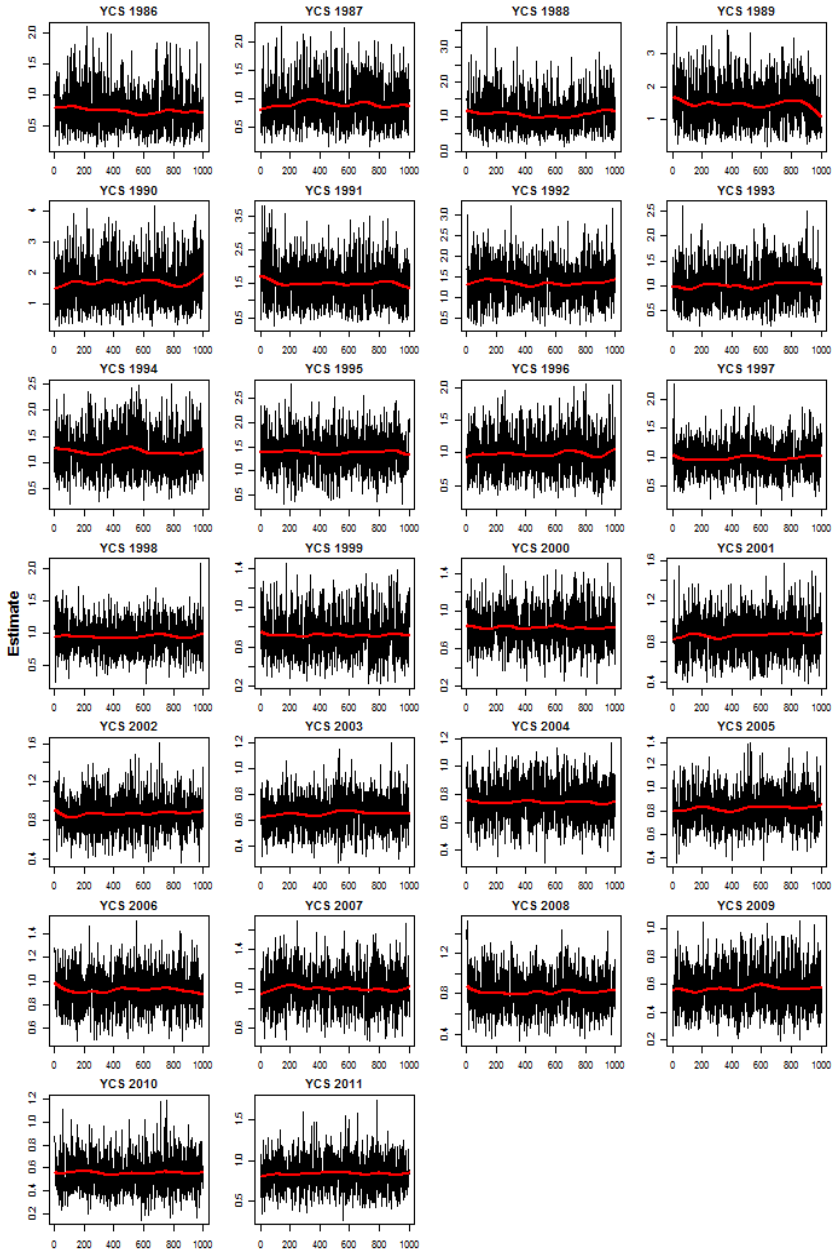
8. MPD fits: Likelihood profile for B0



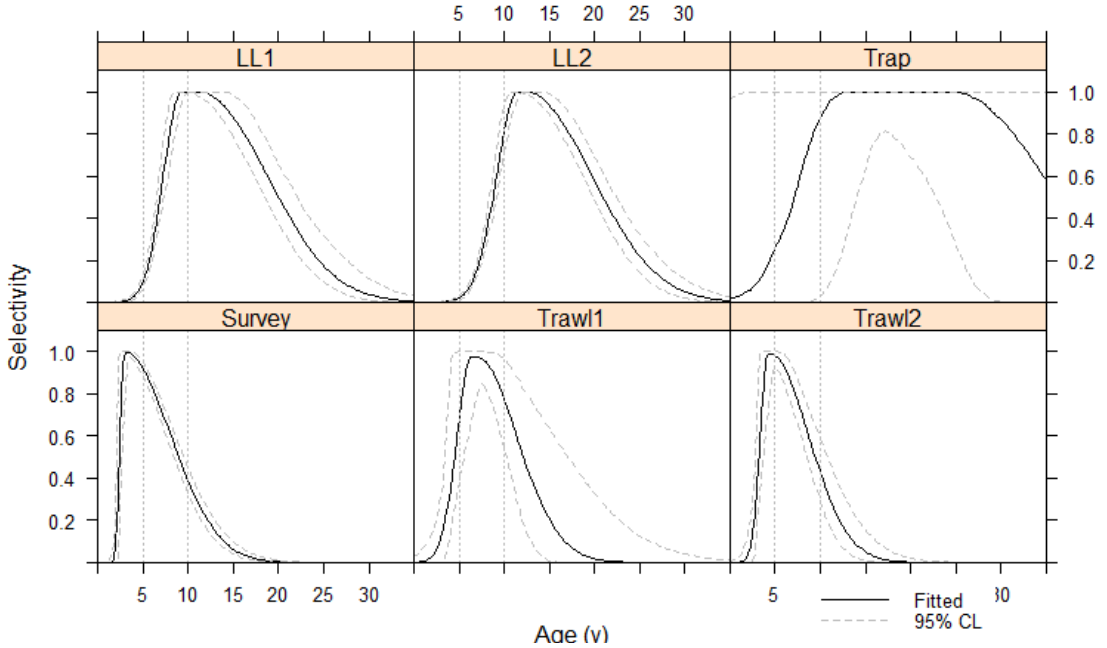


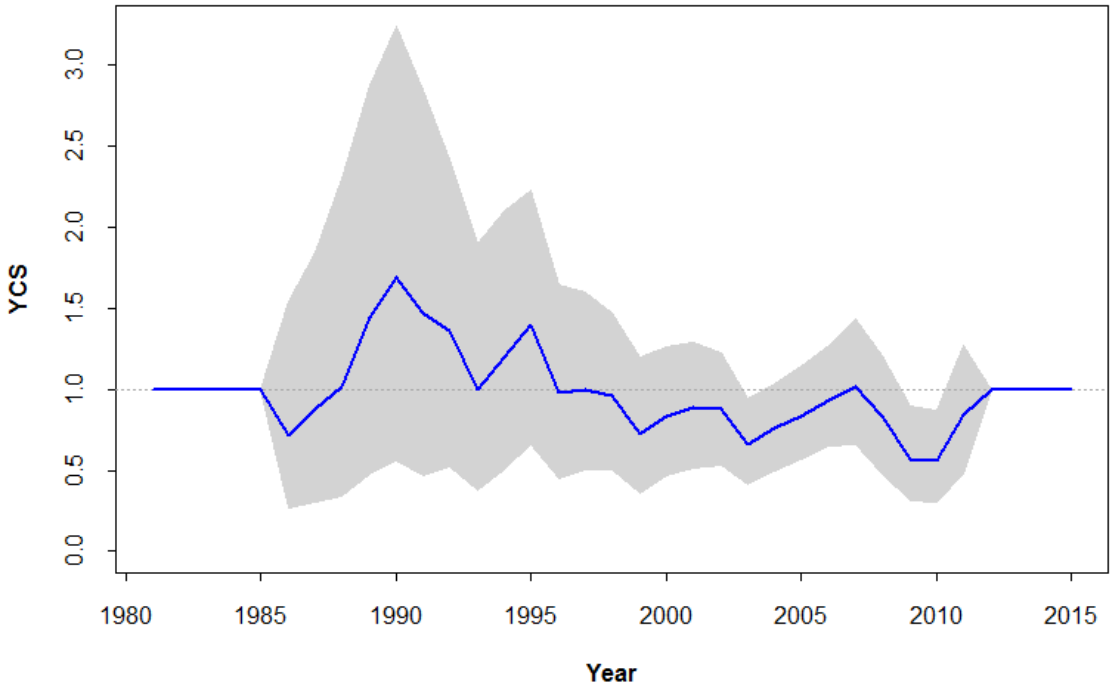
9. MCMC results: Traces





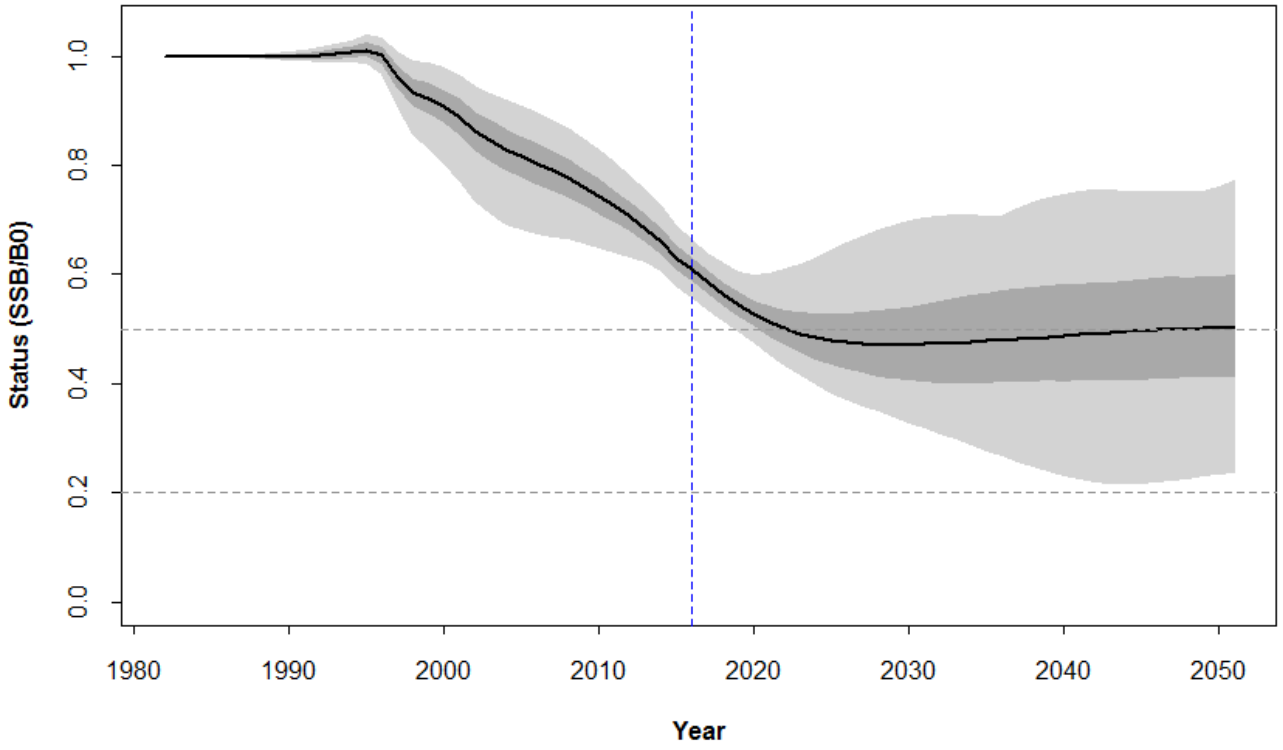
9. MCMC results





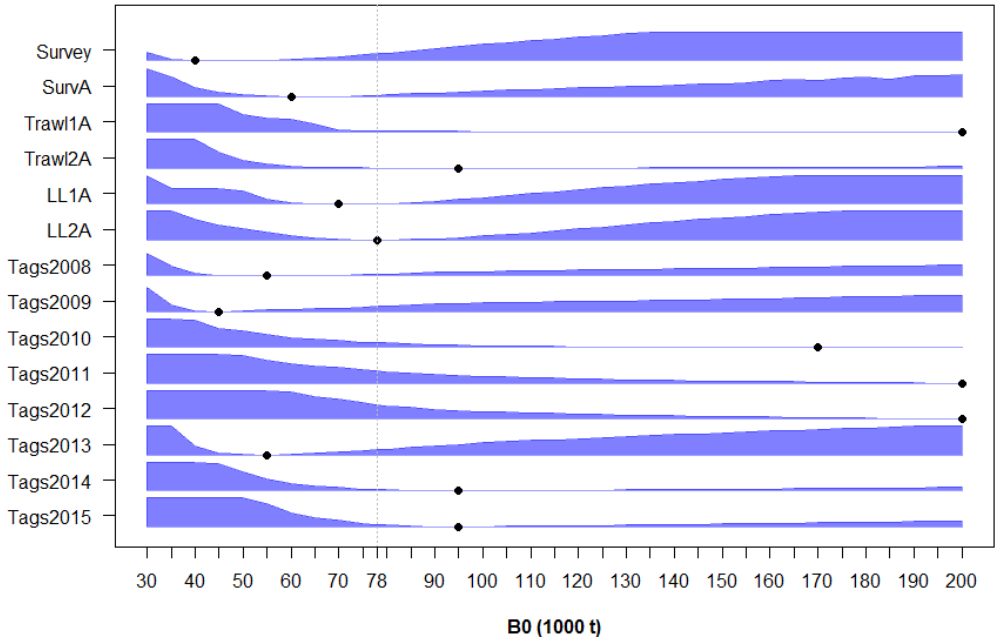
9. MCMC results

Model	B_0	*SSB* Status	Catch limit
2015 Assessment	87 077 (78 500-97 547)	0.64 (0.59-0.69)	3405 tonnes
2017 Assessment	**77 286 (71 492-84 210)**	**0.61 (0.58-0.64)**	**3525 tonnes**

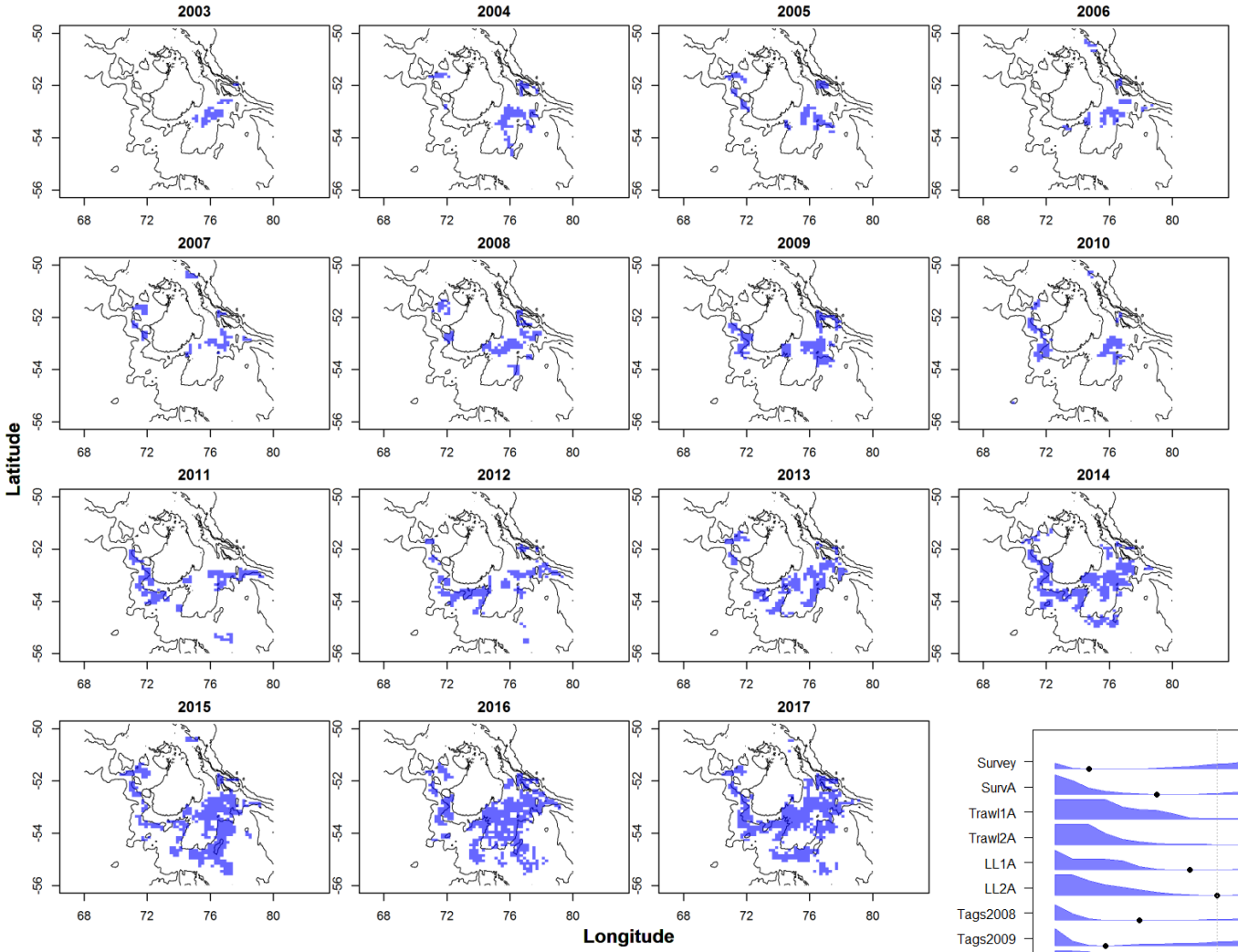


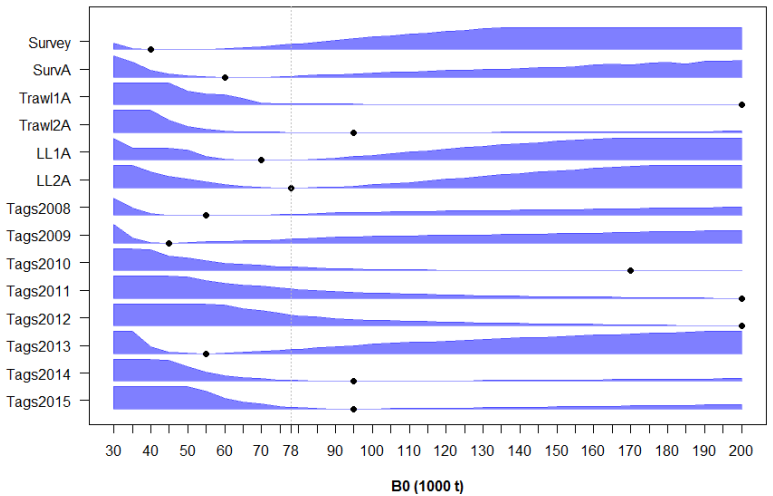
10. Sensitivity analysis

Sensitivity run	B_0	SSB status	R_0	ObjFun
Reference: Model 7	78 845	0.62	6.12	1301
M = 0.13	103 403	0.63	4.69	1313
Estimated M = 0.158	76 209	0.61	6.36	1305
Maturity +2 years for stage-2 fish	79 414	0.61	6.12	1301
Estimated tag dispersion by year of release	75 688	0.60	5.88	1278
Include longline tagging data from 2008+	77 988	0.61	6.06	1759*
Include longline tagging data from 2010+	81 323	0.63	6.32	1540*



10. Sensitivity analysis





10. Future work

- Re-evaluate **maturity-at-age** function (WG-FSA-17, para. 3.48)
- Evaluate potential long-term implications of **declining trend in *YCS***
- Evaluate impact of **dome-shape selectivity** assumptions on the proportion of cryptic biomass, including in relation to maturity proportions at age (WG-FSA-17, para. 3.52)

- Evaluate **sex-based** population model
- Evaluate **spatially-explicit** model (e.g. account for spatial effects of distribution of fishing effort and tagged fish and include more tag-recapture data in model - initial explorations have not indicated meaningful results so far)