Management procedure evaluation for the Indian Ocean skipjack tuna fishery : model description and conditioning

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Abstract

A simulation model of the Indian Ocean skipjack tuna fishery was developed for the evaluation of alternative fisheries management procedures. The model partitions the skipjack population by three regions, 24 quarterly ages, and fourty, 2cm size bins and the fishery by three regions and four gear types (purse seine, pole-and-line, gill net, others). Where possible, parameter estimates from the 2014 stock assessment for skipjack have been used. For those parameters not estimated or assumed in the assessment (e.g. regional recruitment dispersal, movement) prior distributions are used along with constraints to exclude infeasible parameter combinations.

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1 Introduction

This report describes the development of a simulation model of the Indian Ocean skipjack tuna fishery. This work has been progressed by the Maldives pole-and-line fishery in partial fulfillment of the conditions of its Marine Stewardship Council (MSC) certification. Adam et al (2013) provided a background and rationale for the project.

This document outlines the structure of the model, describes prior probability distributions and sensitivity ranges for model parameters, model outputs, fits to data and a preliminary examination of alternative reference points. The model is still under development and requires further refinement and testing. The results presented here are mainly to illustrate the structure of the model and should be considered preliminary.

2 Structure and assumptions

The following convention is used for assigning symbols in the following model equations: Greek lower case letters (e.g. α) for model parameters, Roman capital letters (e.g. N) for model variables, and Roman lower case letters for variable or parameter array subscripts (e.g. $N_{r,a,s}$, φ_r). Using this convention means that in some instances model parameters are given different symbols that usual. However, it has the advantage of clearly distinguishing model parameters (which are independent of other parameters or variables and are usually estimated) from model variables (which are dependent upon parameter values).

The subscript for time, t, is usually omitted from the model equations below except where it is necessary to be explicit regarding the time step involved.

2.1 Dimensions

Several dimensions are used to partition aspects of the model (e.g. fish numbers, catches). See Table 1 for symbols used for each.

The model uses a quarterly, i.e. three month, time step (t). Each time step, t, has an associated calendar year (y) and calendar quarter ($q \in 0, 1, 2, 3$).

There are three regions (r), West (we), Maldives (ma) and East (ea) (Figure 1). The term "region" is used in preference to "area" because using the latter would confound the a subscript which is also used for age. The three regions were mostly defined based on difference is the main fishing gears used in each. There is little information available on biological stock definitions for Indian Ocean skipjack tuna. However, based on what is available, #fontaneau-2014-skj-stocks, suggested four regions, in which the western region is divided into northern and southern regions at the equator. Given the nature of the catch distribution and resolution of available data, this four region definition should be relatively straightforward to use in future revisions.

Fish recruit to the model in each quarter and the model keeps track of their numbers by their age (a), in quarters up to six years i.e. $0, 1, 2, ..., 23$. Fish size (s) is represented in forty, 2cm bins, $0-2, 2-4, ..., 78-80cm$

Four fishing methods (m) are defined : purse seine (ps), pole and line (pl), gill net (gn) and other (ot). There are differences in the size distribution of free-school and associated-school purse seine sets. However, given the low proportion of free-school sets, particularly in recent years, it was considered unnecessary to model these subcomponents separately.

Table 1: Summary of model dimensions and symbols used for each.

Time	
t	Time step
y	Calendar year
q	Calendar quarter; 1 = Jan-Mar
Regions	
r	Region subscript
we	West region
ma	Maldives region
ea	East region
Fish age and size	
a	Fish age group
$\overrightarrow{a}$	Maximum age in the model
s	Fish size group
$\overrightarrow{s}$	Largest size group in the model
Fishing methods	
m	Fishing method subscript
ps	Purse seine
pl	Pole and line
gn	Gill net
ot	Other

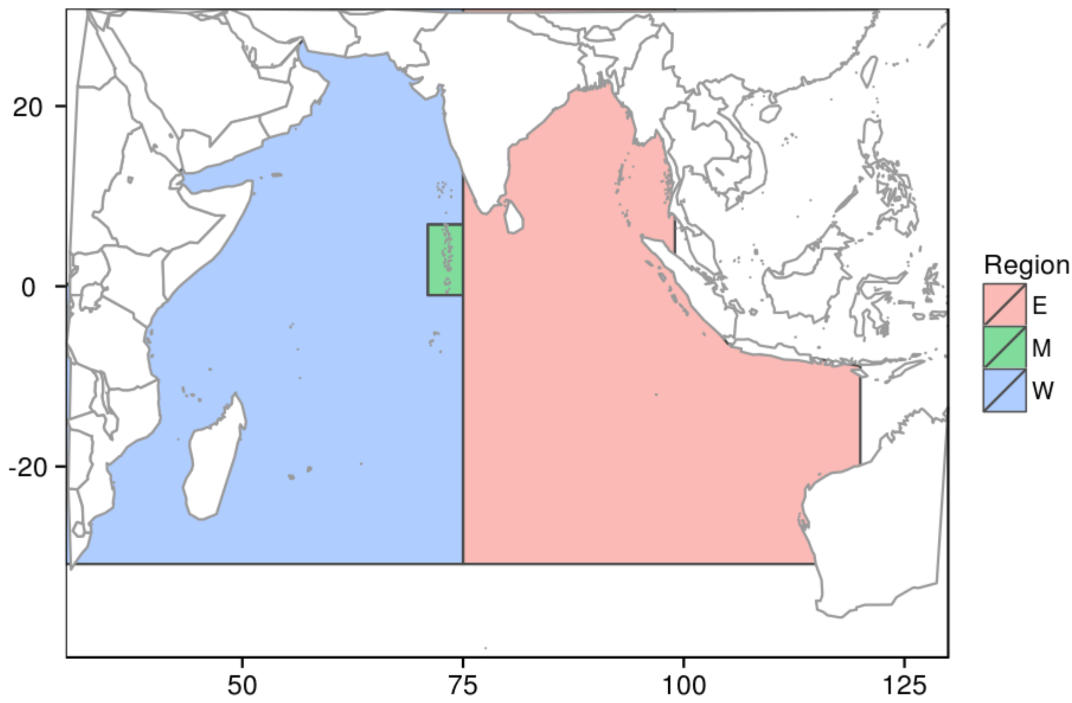


Figure 1: Map of the three regions used in the model: Western (W,we), Maldives (M,ma), Eastern (E,ea).

2.2 Fish

2.2.1 Numbers

Fish numbers are partitioned by region, age and size, $N_{r,a,s}$. In each quarter, recruitment to the model and ageing occur as follows.

The maximum age group, $\overrightarrow{a}$, accumulates fish from the previous age, $\overrightarrow{a} - 1$,

$$N_{r,\overrightarrow{a},s} = N_{r,\overrightarrow{a},s} + N_{r,\overrightarrow{a}-1,s}$$

For ages 1 to $\overrightarrow{a} - 1$, simple ageing occurs,

$$N_{r,a,s} = N_{r,a-1,s}$$

For age 0, recruitment occurs,

$$N_{r,0,s} = R_{r,s}$$

where $R_{r,s}$ is the number of fish recruiting to age 0 in region r at size s.

Numbers are updated by applying growth, survival, exploitation and movement. The numbers in each region, in each age class and size class are determined by summing over all regions and size classes,

$$N_{r,a,s} = \sum_{\dot{r} \in \{we,ma,ea\}, \dot{s}=0 \ldots \overrightarrow{s}} \left(\dot{N}_{\dot{r},a,\dot{s}} G_{\dot{s},s} D \left(1 - E_{\dot{r},\dot{s}}\right) M_{\dot{r},r} \right)$$

where is the growth transition matrix, is the natural survival rate, is the exploitation rate, and is the movement transition matrix (all described below).

2.2.2 Length, weight and maturity

The length of fish of size is the midpoint of the 2mm bin size,

The weight of fish of size is modelled as an exponential curve,

Currently, the model assumes that the parameters of the length-weight relationship are the same in the three regions. These seems a reasonable assumption, but it is possible that condition factors consistently vary among regions, in which case these parameters could be made to vary by region i.e.

The proportion of fish of size that are mature is modelled as a logistic curve,

Currently, the model assumes that the parameters of the maturity curve are the same in all three regions but could be made to vary by region i.e . In addition, maturity could be modelled as a function of age, rather than size, i.e. .

2.2.3 Spawning and recruitment

The proportion of mature fish that spawn in each quarter is allowed to vary according to a quarterly parameter, . Currently, this parameter is the same for all regions. Evidence of regional differences in spawning seasonality would suggest making these parameters vary by region.

The biomass of mature fish is a function of the number of fish by age and size and the maturity and weight ogives by size,

We refer to this varable as the biomass of spawners and is used as the basis for determing stock status, .

Recruitment occurs in each quarter and is partitioned by region and size, . The total number of eggs is based on the total spawning biomass in the previous quarter,

where is the proportion of fish that are mature at size , is the weight of fish at size , and is the proportion of fish that spawn in quarter .

The total number of eggs determines the total number of recruits over all three regions, using the Beverton-Holt stock recruitment function,

where is steepness, and are the respectively the number of recruit and eggs in the absence of fishing, and is the recruitment deviation at time t which is lognormally distributed with mean of 1 and standard deviation of .

This total recruitment is distributed across the three regions,

where is the proportion of recruits which recruit into region and is the proportion of recruits of size which is based on a normal distribution with mean, and standard deviation ,

2.2.4 Natural mortality

The instantaneous rate of natural mortality at size is modelled as a function of weight at size using the form of Lorenzen,

To prevent going to very high levels at low , is restricted to be a maximum of (i.e. the mortality at size bin 10, i.e. length of 21cm).

The survival rate in one quarter is,

2.2.5 Growth

Growth is described using a size transition matrix which is calculated based on the von Bertallanfy growth function. The mean increment in one quarter is,

Variation in growth is modelled as a normal distribution with a constant standard deviation, , and a coefficient of variation, , on the increment. The standard deviation of the growth increment for a fish of size is thus,

The proportion of fish growing from size to size in one quarter is thus,

At present, it is assumed that growth is the same in all three regions. It is likely that in fact growth differs between regions in which case some, or all, of the growth parameters could vary by region e.g , .

An alternative to the von Bertallanfy function would be to use the two-stanza growth model and parameter estimates of Everson et al (2012, 2014).

2.2.6 Movement

The proportion of fish moving from region to region in one quarter is described by the movement matrix defined by six off-diagonal parameters,

There could be separate movement parameters for each age (or size) e.g. , or more simply, the relative proportion of fish moving could vary by age (or size).

In summary, at present, whilst the model keeps account of fish numbers by region, only two of the biological characteristics of the stock vary by region: the proportion of recruitment going to each and the movement between each. As noted above, many of the model's parameters could be made to vary by region but this is likely to be of little value without information with which to inform how much those parameters should vary by region.

2.3 Fishing

Selectivity is modelled as a function of length using a piecewise spline with knots at every ten cm from 20cm to 80cm.

Catches are compiled by region and method, from IOTC data. The biomass that is vulnerable to each method, in each region , is calculated by summing over ages and sizes,

where is the relative selectivity of method for fish of size, .

The exploitation rate in region of method is then,

3 Implementation

The source code for this project is managed using the Git distributed version control system and is publicly available at https://github.com/iotcwpm/SKJ. The `README.md` file of the repository provides a useful entry point for understanding the organisation of the code.

The model has been implemented using the C++ programming language. C++ was chosen for its high computational speed, considered an important requirement for a model of this complexity, which is to be used to evaluate numerous candidate management procedures, several thousand times. The C++ code is generally well documented and web navigable documentation, generated using the tool Doxygen, is available at http://iotcwpm.github.io/SKJ/doxygen/. As the model is being refined this documentation is updated and as such it should be considered more up-to-date than the above descriptions and equations which may have been superseded.

In addition to the core C++ code, R scripts for the preparation of input data and for the generation of output summaries are available in the repository.

4 Parameter priors and sensitivity ranges

For each model parameter a prior probability is defined. These priors are used in conditioning algorithms and are intended to represent the prior knowledge and associated uncertainty regarding a parameter. For some parameters, such as stock recruitment steepness , there is unlikely to be any information in the data and so the prior may be influential.

In addition, for each model parameter a sensitivity range is defined. This range is used in robustness testing of candidate harvest control rules to evaluate how sensitive a rule is to parameter values which are possible but which are determined, on the basis of either priors or conditioning, to be unlikely. In the current iteration of this project, this type of rubistness testing has not been implemented, and hence the sensitivity ranges proposed in this section have not be used.

At present, only some of these prior distributions are used in conditioning because parameter estimates from the latest stock assessment are being used where possible. However, for those parameters which are not estimated or assumed in the assessment (e.g. movement parameters), these priors will be of relevance. The priors described here should not be considered definitive and ideally should be be refined in consultation with a wider group of Indian Ocean tuna scientists. As much as anything, the utility of this section is in providing some documentation on the information available to inform parameter priors.

4.1 Weight and maturity

Priors for length-weight parameters, alpha and beta, were based on the fixed values used in Sharma et al (2012) with a coefficient of variation of 5% (Table 2).

Priors for maturity ogive parameters, and were based on the results of Grande (2013). For the inflection point, , based on Grande's estimated a value of 39.9cm, a normal prior with mean of 40cm and a coefficient of variation of 5% was used. Note that Table 4.2 of Grande (2013) indicates that some earlier studies in the Indian Ocean estimated values around 42-43cm for the inflection point. Sharma et al (2012, 2014) assumed 38cm based on Grande et al. (2010).

Figure 7.3 of Grande (2013) shows 5% and 95% maturity at about 35cm and 44cm respectively. Given a 50% maturity of 40cm this corresponds to a steepness parameter, upsilon, of about 5cm. A normal distribution with a mean of 5cm and a 10% c.v. was used (Table 2).

4.2 Spawning and recruitment

In the western Indian Ocean, skipjack spawning appears to occur all year but with periods of greater activity during the North-east monsoon (November to March) and South-west monsoon (June to July) (Grande 2013 and references cited therein). Grande (2013) summarised the percentage of fish in the "spawning capable" phase in the months January to July. This percentage was highest during January and February (85%) decreasing to 51.9% in May and then increasing again to 82.4% in June and 73.3% in July. These percentages were used as the basis for a uniform prior on each rho_q (Table 2). We assumed that the spawning percentage during the fourth quarter, October to December, was the same as during the second quarter.

Following Mangel et al. (2010) the prior for stock-recruitment steepness is based on a beta probability distribution function for a precursor parameter

where B(.) is the beta distribution. This formulation allows for eta to be constrained between 0.2 and 1. The resulting prior for steepness has a median of 0.84 and 5, 20, 80 and 95th percentiles of 0.67, 0.76, 0.9, 0.93 respectively.

For the standard deviation of stock-recruitment deviations, a lognormal prior with a mean of 0.6 and a standard deviation of 0.5 was used based on Myers (2002) Figure 6.5 which has a median of about 0.6 for Scombridae.

4.3 Mortality

The instantaneous rate of natural mortality at 1kg, , the same normal prior as in Sharma et al (2012) was used which has a mean of 0.8 and a standard deviation of 1 (Figure X).

A prior for the allometric exponent of the weight to natural mortality function, was based on Lorenzen (1996) who estimated a value on -0.29.

4.4 Growth

The priors for the growth curve parameters were from Hillary (2011). His Table 2 provides estimated posterior distributions for , and from analysis of tagging data. For comparision, Sharma et al(2012) assumed 0.37 and 70 for , based on Anganuzzi & Million (pers. comm.).

Hillary's estimate of 78.8 for seems to be very high given that this is a coefficient of variation an hence needs to be multiplied by the increment to calculate a standard deviation (although note that Hillary's Equation 1 says multiplied by the length).

4.5 Movement

There is little quantitative information on movement rates between the three regions. A uniform prior, was used for all elements of the movement matrix

4.6 Selectivity

Priors for selectivity parameters were based on estimates from the previous assessment (Figure 1 of Appendix 2 in Sharma et al 2012).

Table 2: Prior probability distributions and sensitivity rages for model parameters. Note that this table may be incomplete. Distributions are indicated as follows: fixed , uniform , normal , lognormal , beta , mesa

Symbol	Description	Units	Prior distribution	Sensitivity range
Weight				
	Coefficient of the length-weight relationship			4-6
	Exponent of the length-weight relationship	-		3.0-3.6
Maturity				
	Inflection point of the maturity ogive			35-55
	Steepness of the maturity ogive			2-10
Spawning				
	Proportion of mature fish spawning in quarter	-		
Recruitment				
	Virgin recruitment	-		
	Steepness of the stock-recruitment relationship precursor parameter	-		
	Standard deviation of stock-recruitment deviations	-		
	Proportion of total recruits that recruit into region	-		
	Mean length of fish at the end of the first quarter	-		
	Standard deviation of the length of fish at the end of the first quarter	-		
Natural mortality				
	Instantaneous rate of natural mortality at a weight of 1kg			0.4-1.0
	Exponent of weight to natural mortality rate function			[-0.2,-0.4]
Growth				
	Mean size of fish in their first quarter			
	Standard deviation of fish in their first quarter			
	Maximum growth rate			0.2-0.4
	Assymptotic length			70-80
	Growth variability			
Movement				
	Proportion of fish moving from region to region			0-1

5 Ouputs

This section presents model outputs generated from the `run` task (i.e. `./ioskj.exe run`) which uses the reference parameter set defined in the `parameters/input` folder. Since those parameter values are user inputs the following may not reflect best parameter estimates. These summaries are primarily intended for illustrating the model struture.

5.1 Recruits size distribution

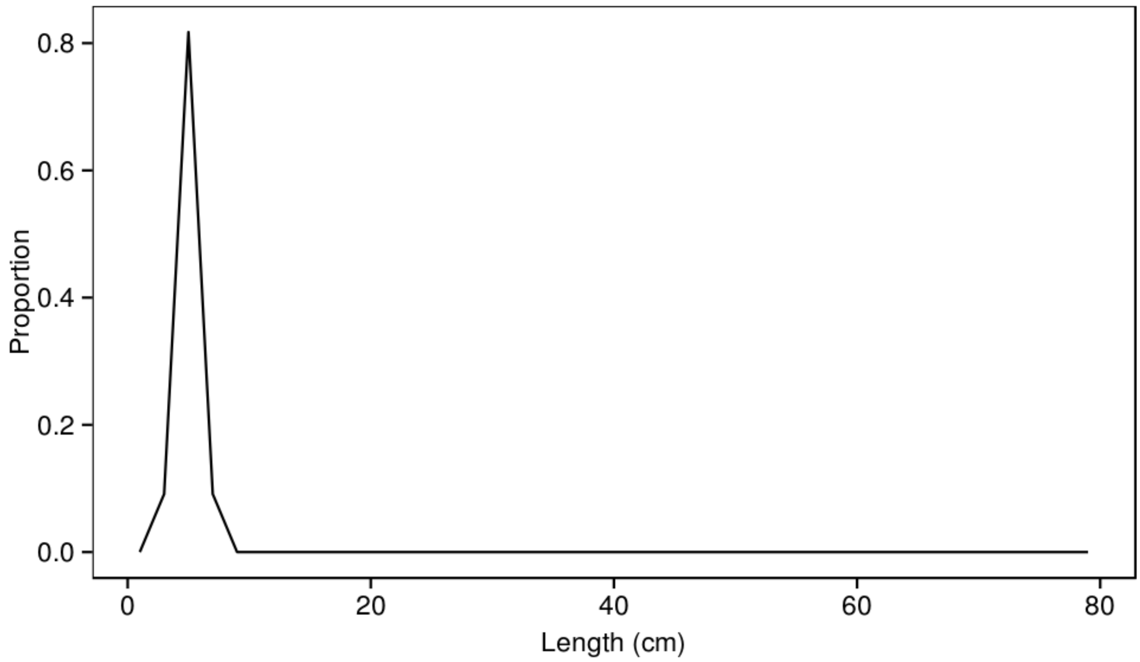


Figure 2: Distribution of the length of recruits. Recruits are added to the model following this distribution.

5.2 Weight and maturity

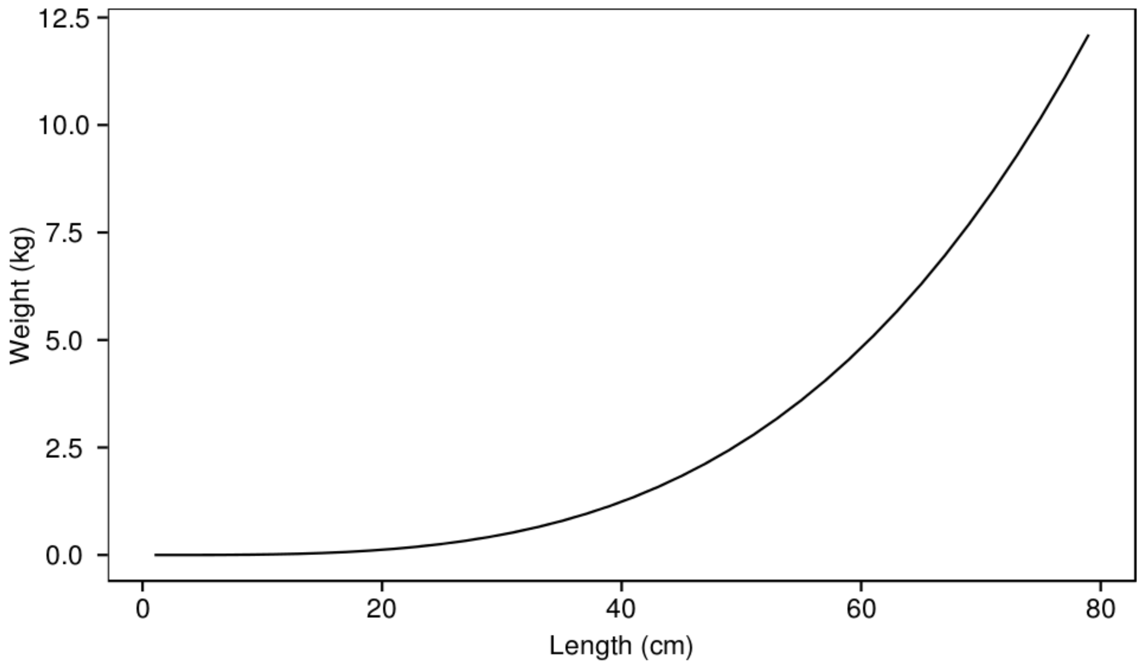


Figure 3: Weight at length.

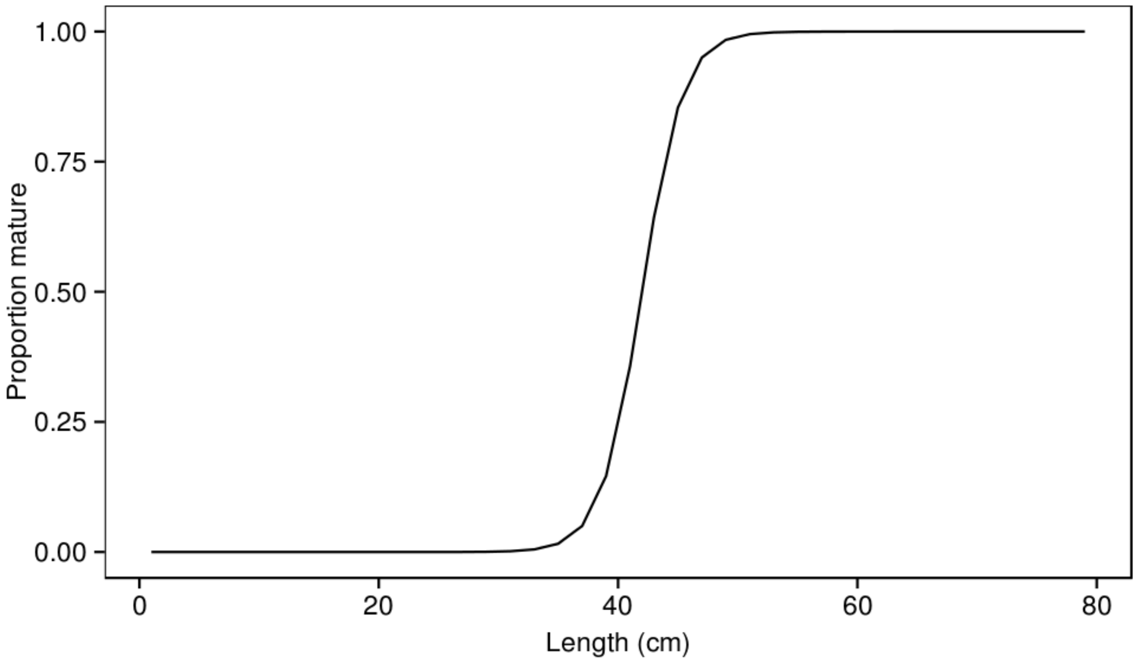


Figure 4: Maturity at length.

5.3 Growth

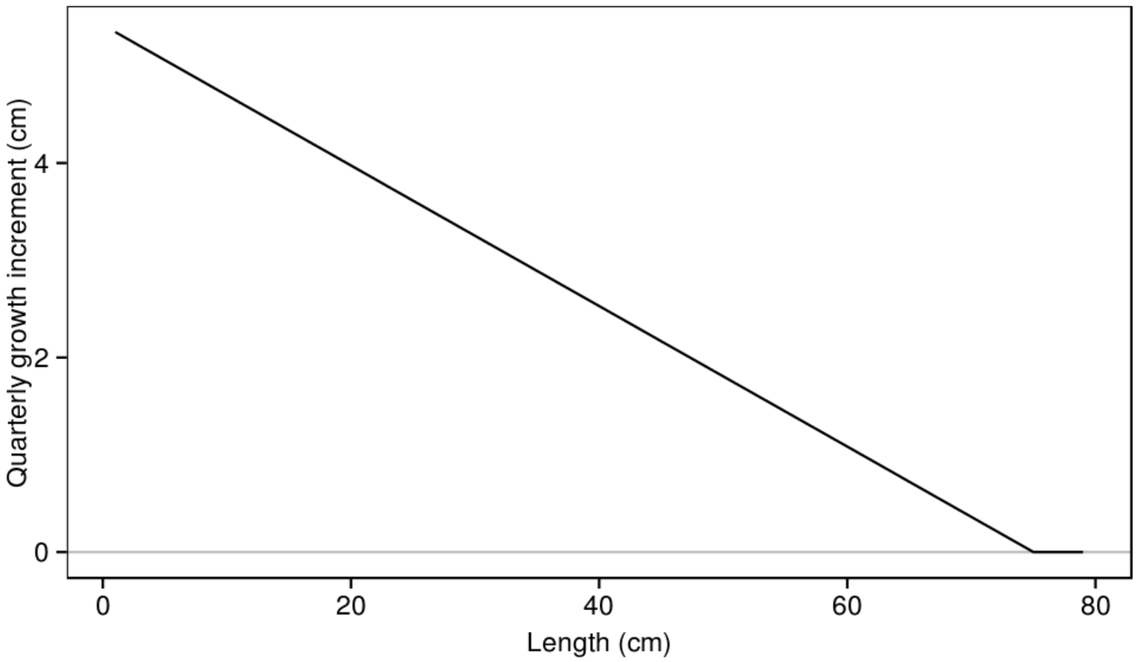


Figure 5: Growth increments by length.

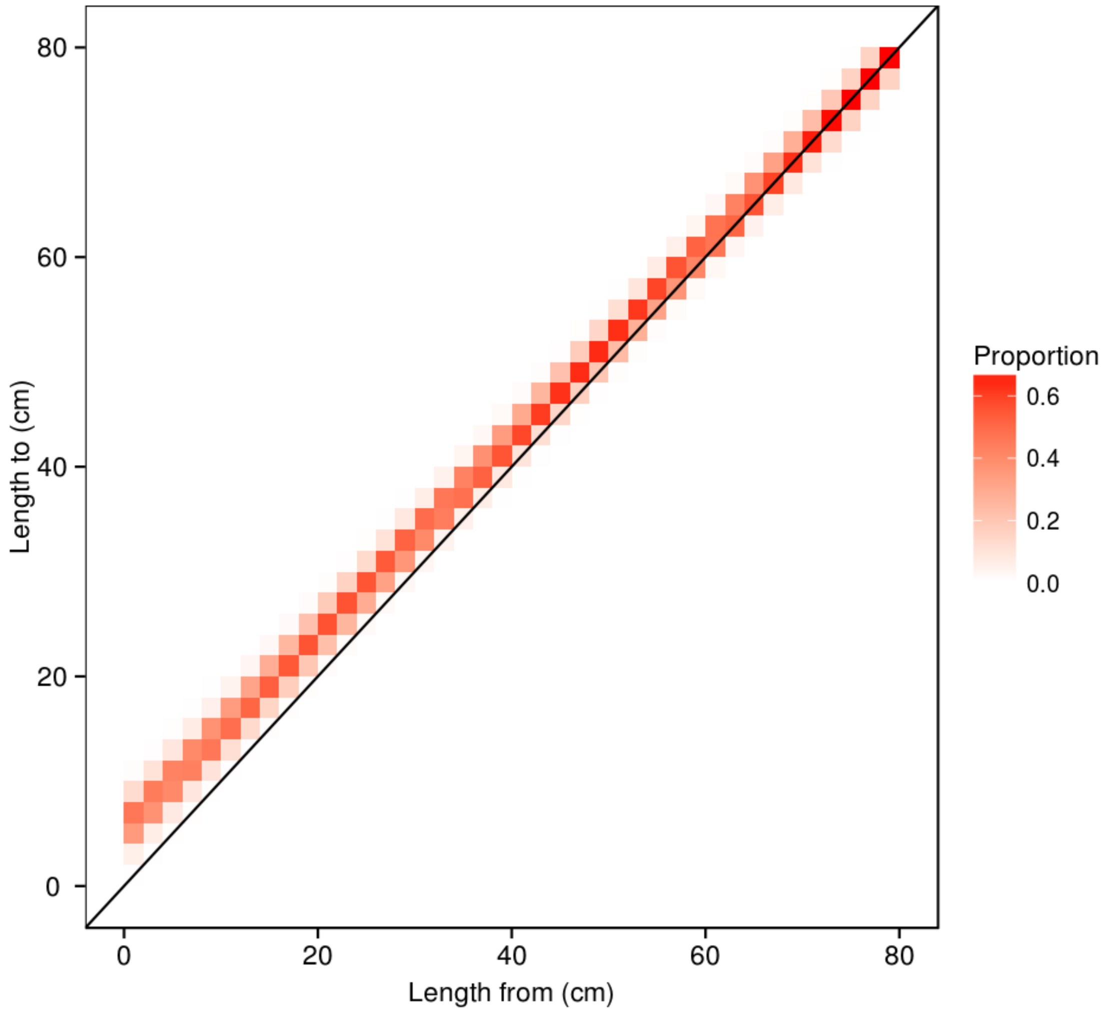


Figure 6: Growth transition matrix indicating the proportion of fish that transition from one length class to other length classes in one quarter.

5.4 Mortality

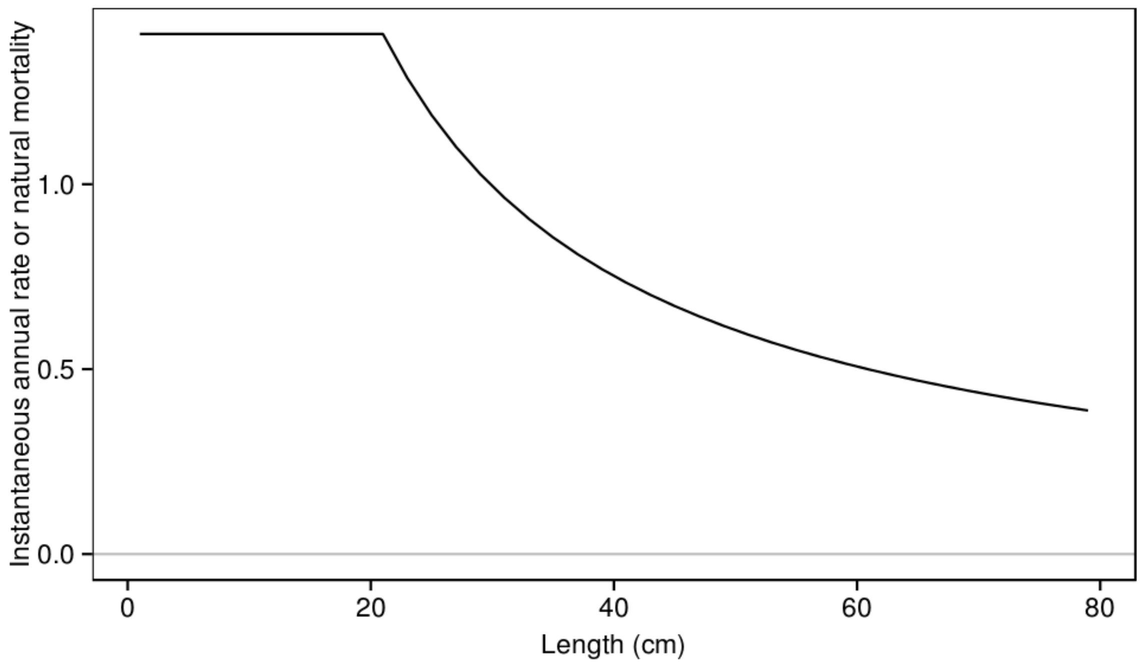


Figure 7: Mortality at length.

5.5 Movement

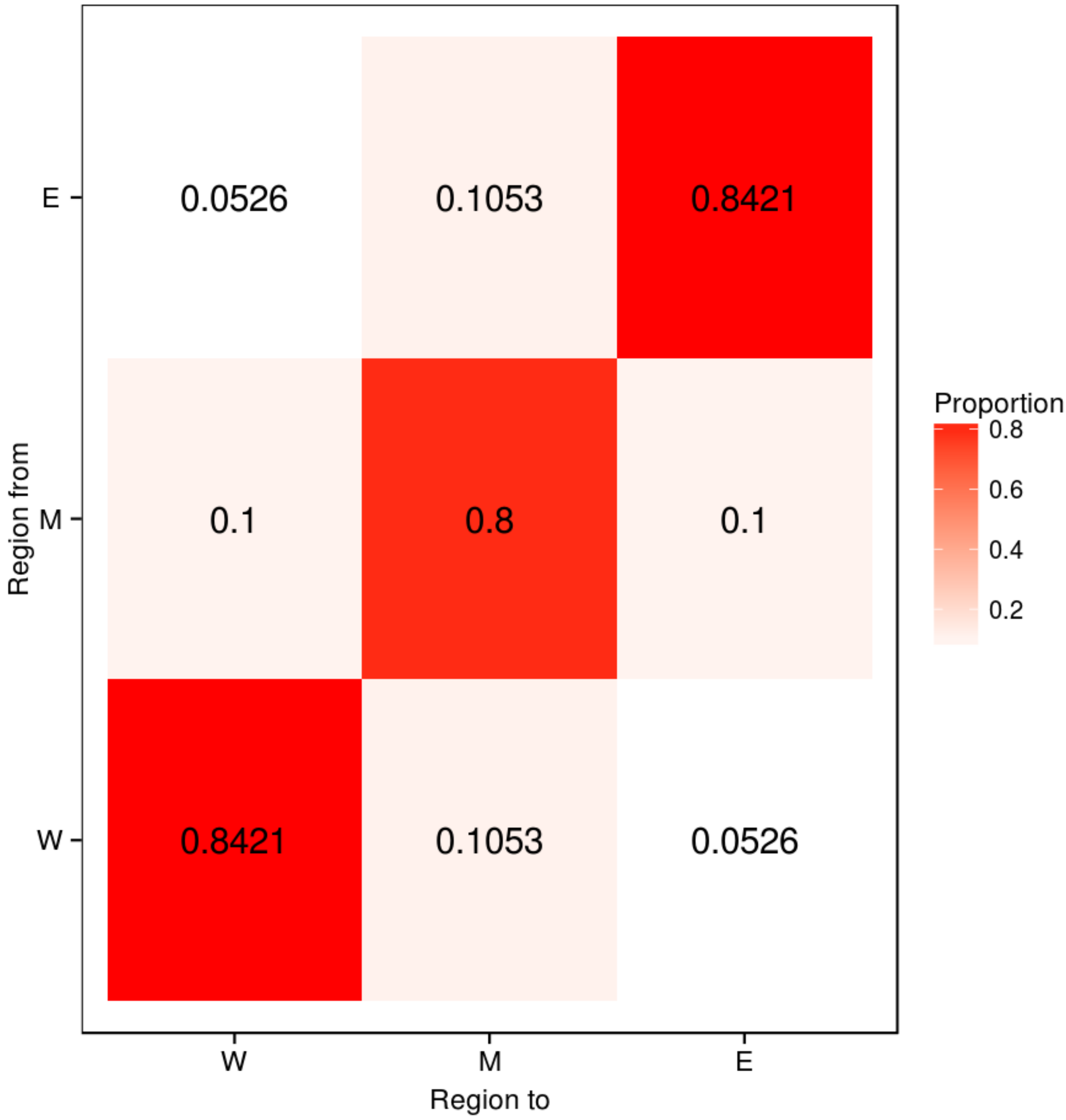


Figure 8: Movement proportion by quarter. Each cell indicates the proportion of fish moving from one region to another in one quarter.

5.6 Selectivities

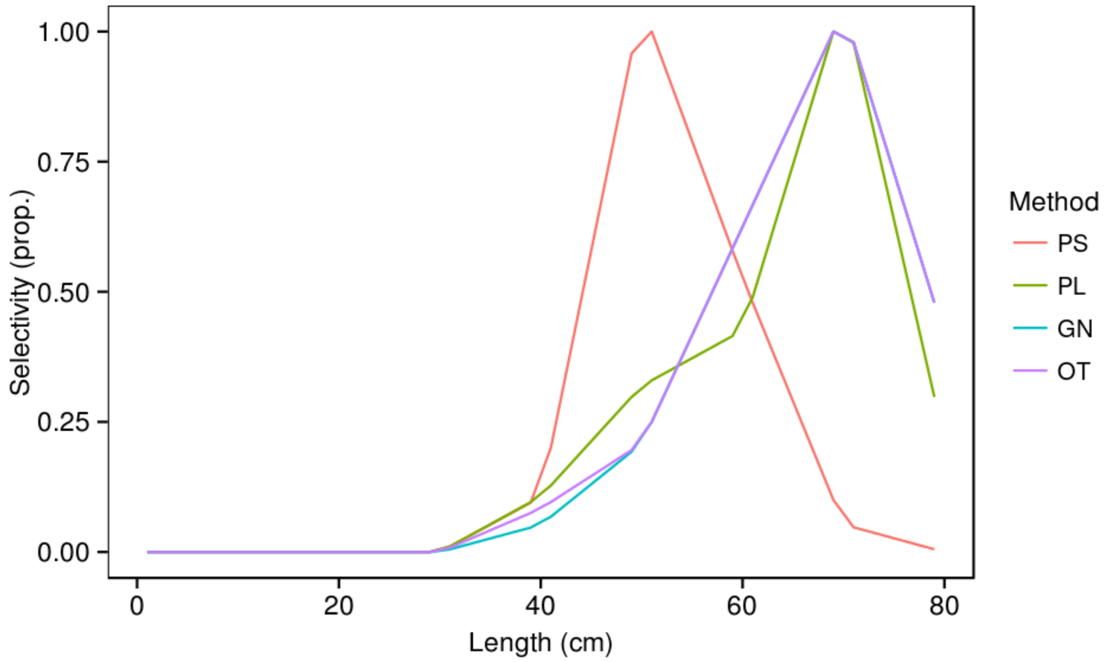


Figure 9: Selectivity at length by fishing method.

5.7 Biomass and recruitment trajectories

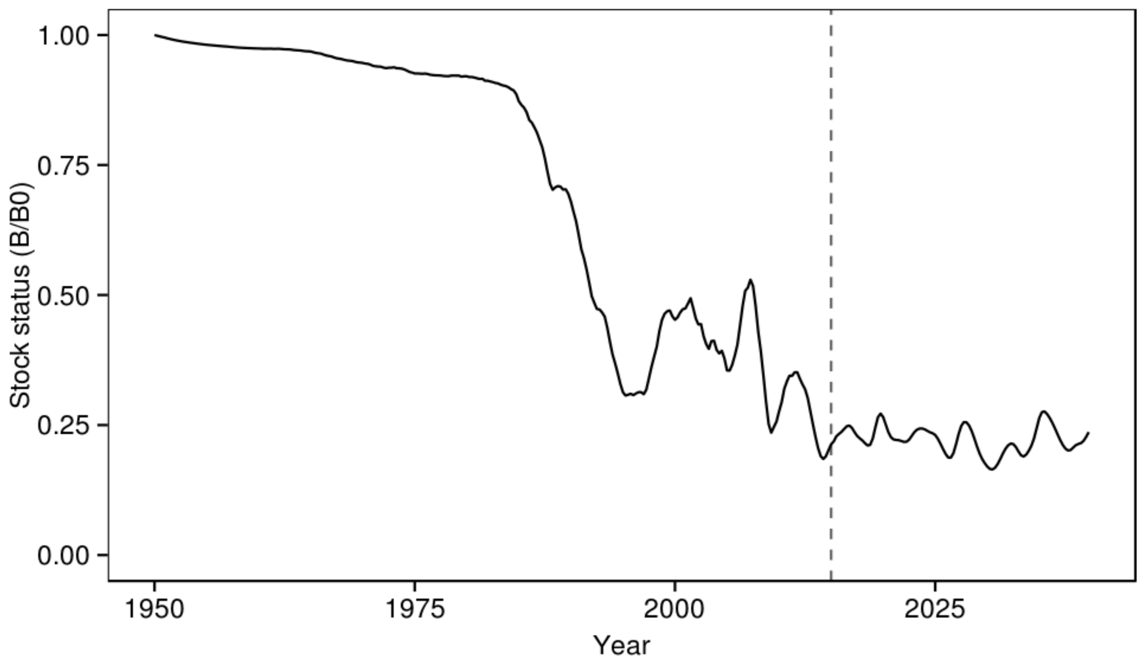


Figure 10: Stock status trajectory.

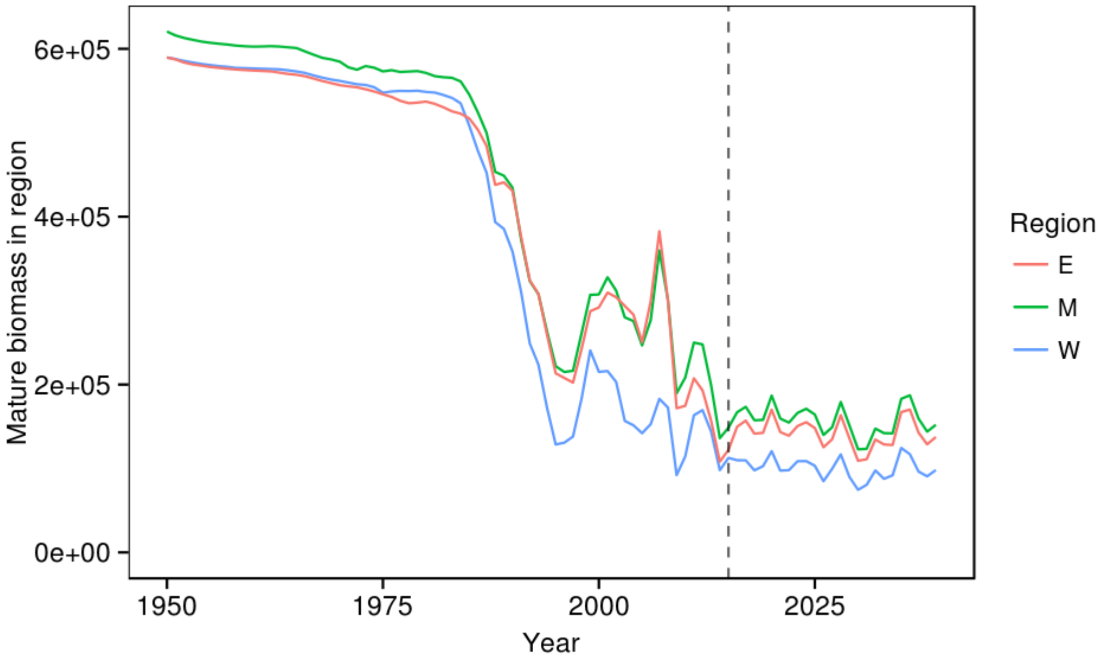


Figure 11: Biomass of spawners by region (first quarter).

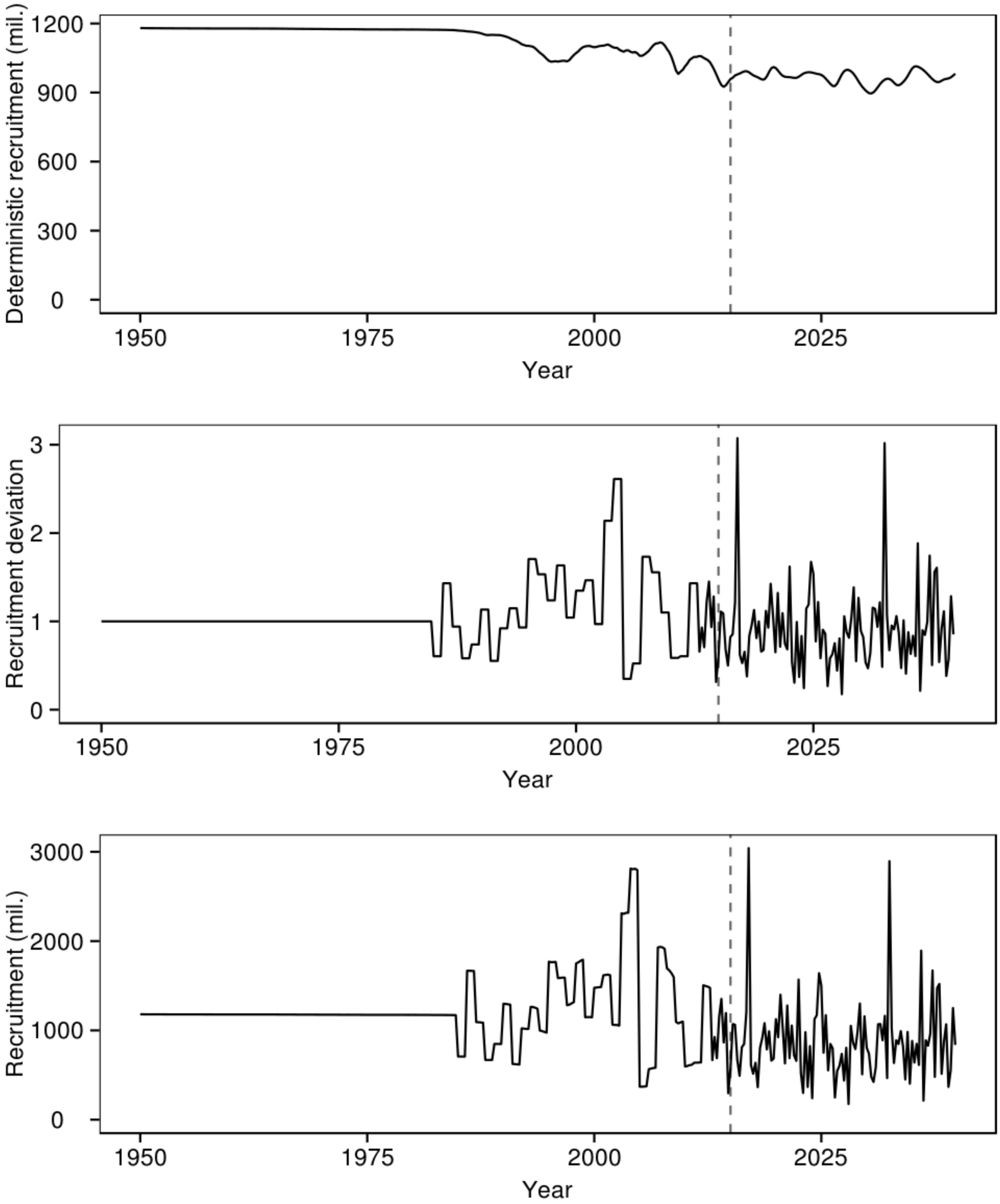


Figure 12: Recruitment trajectories

5.8 Fishery related trajectories

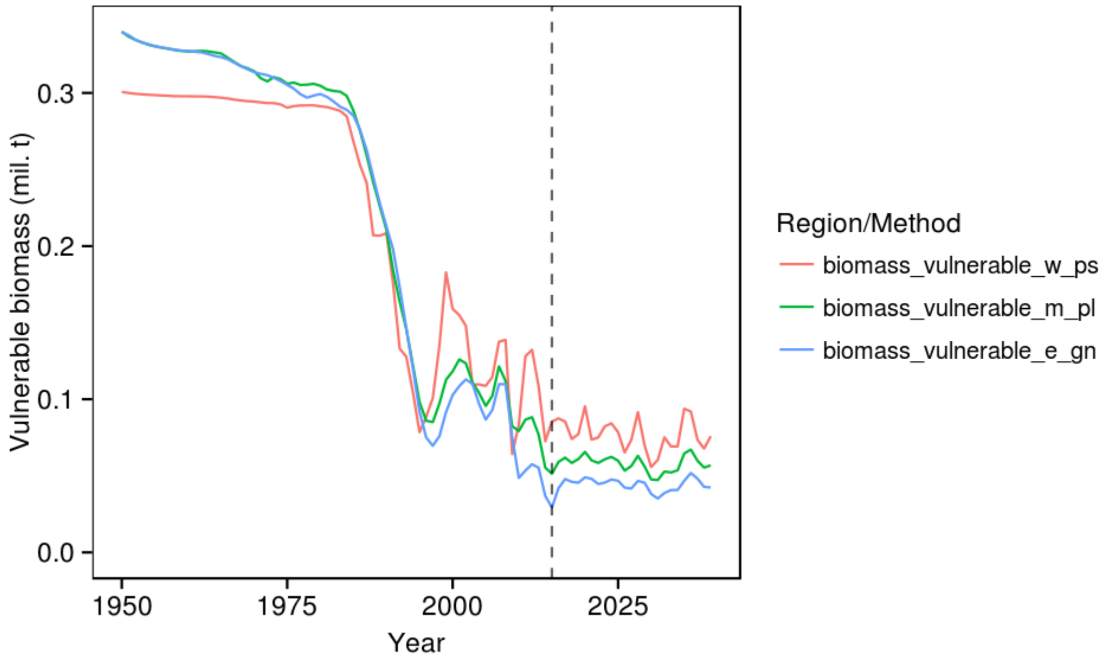


Figure 13: Vulnerable biomass trajectories for the three main fisjeries

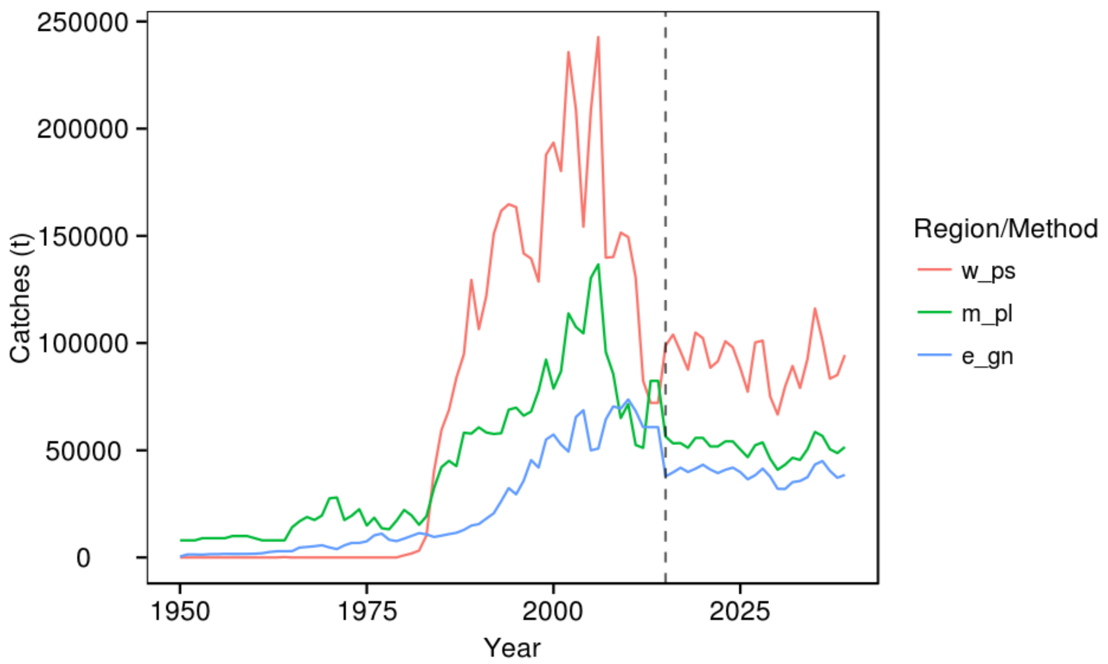


Figure 14: Catch trajectories for the three main fisjeries

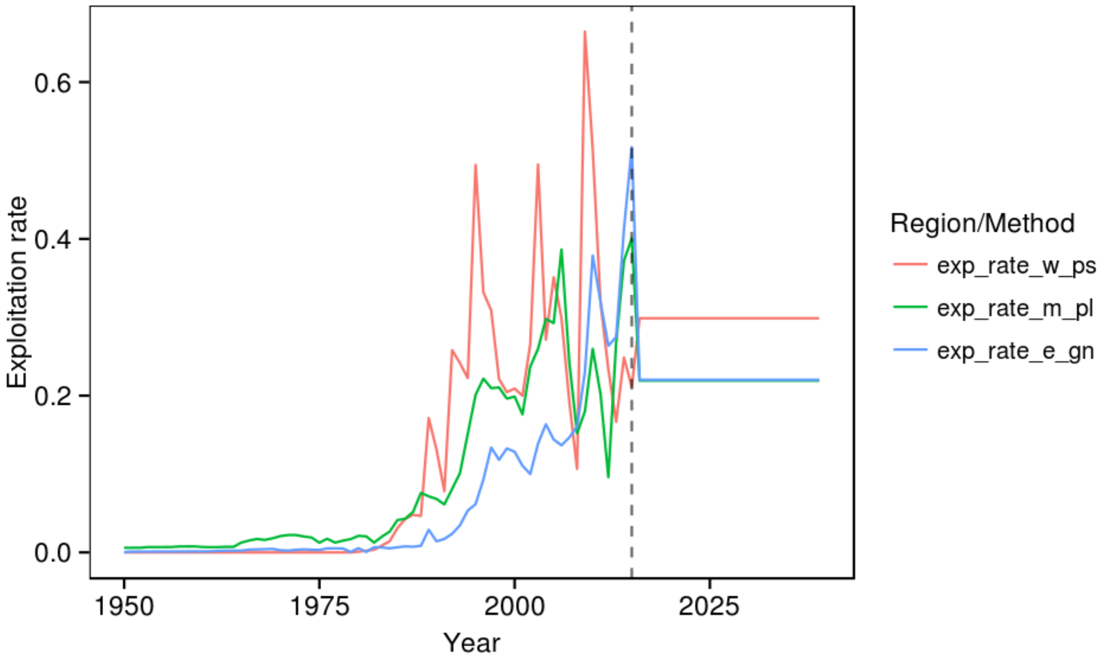


Figure 15: Exploitation rate trajectories for the three main fisjeries

6 Fits to data

This section displays fits to the data generated from the `run` task (i.e. `./ioskj.exe run`) which uses the reference parameter values defined in `parameters/input` folder. Since those values are user inputs the following may not reflect best parameter estimates. In the following plots the lines indicate values expected from the model while the points represent the observed data.

6.1 Maldive pole and line (M-PL) CPUE

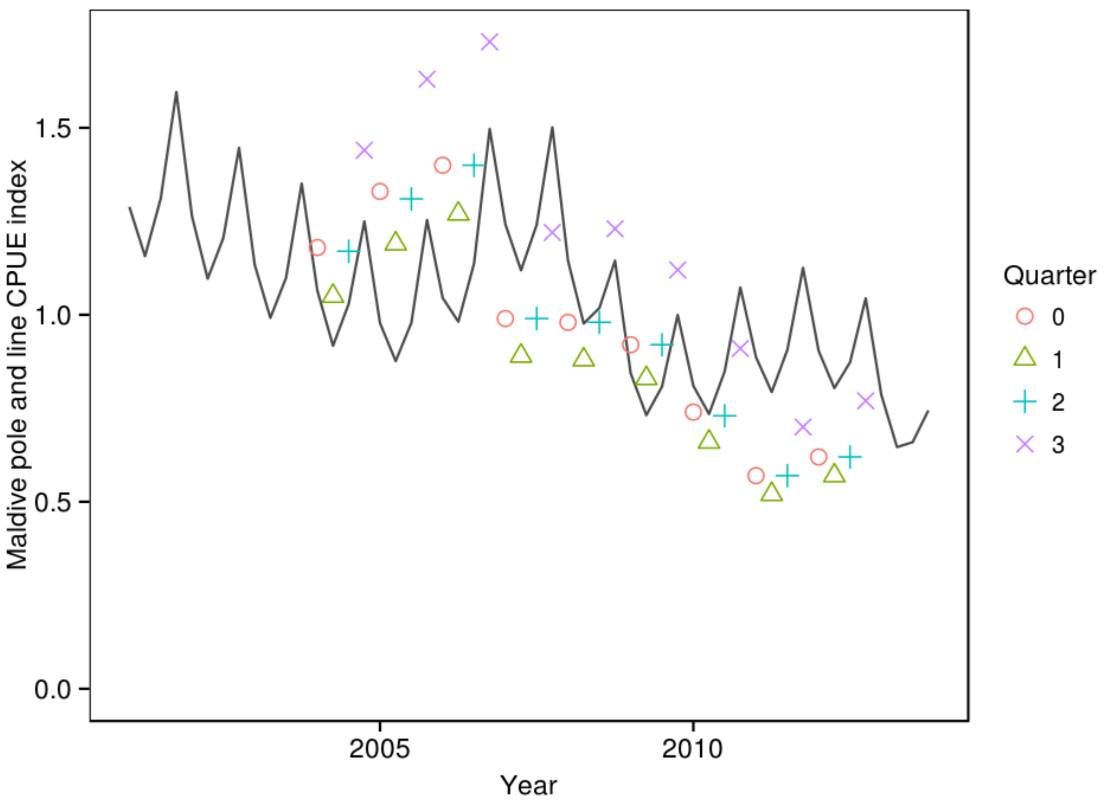


Figure 16: Observed (points) and expected (lines) Maldive (M) pole and line (PL) CPUE.

6.2 Western purse seine (W-PS) CPUE

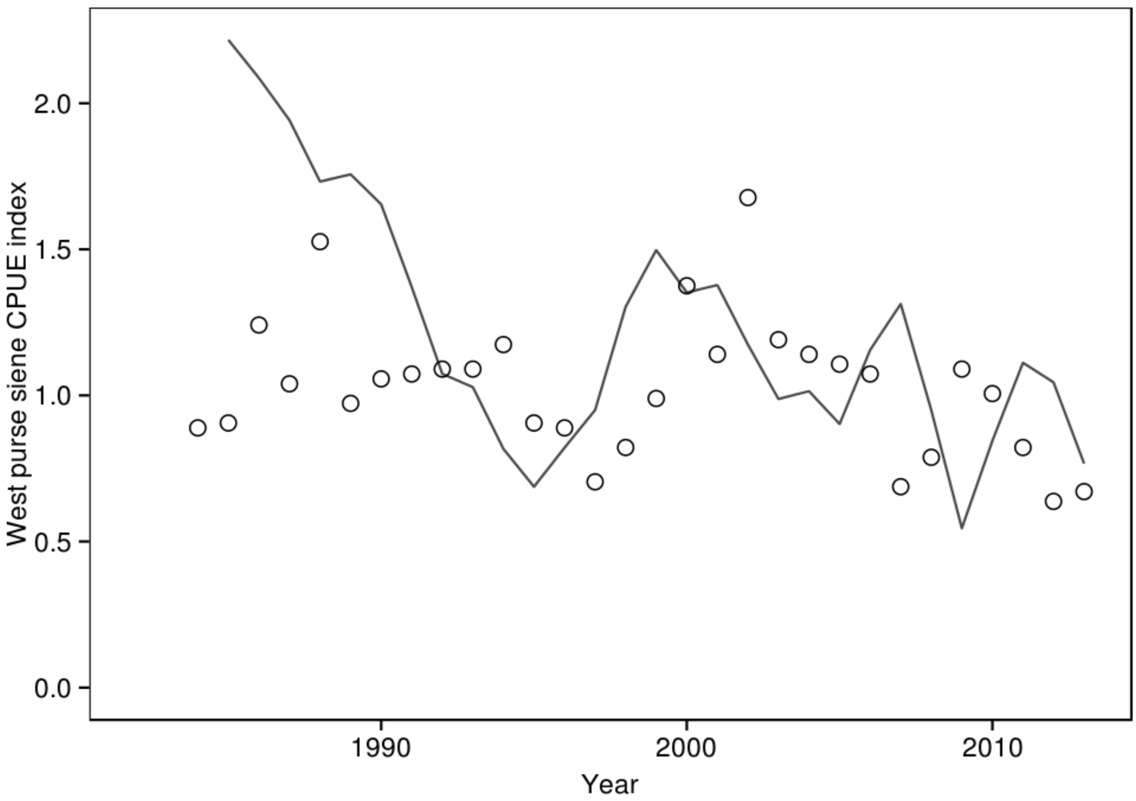


Figure 17: Observed (points) and expected (lines) western (W) purse seine (PS) CPUE.

6.3 Western purse seine (W-PS) tagging Z estimates

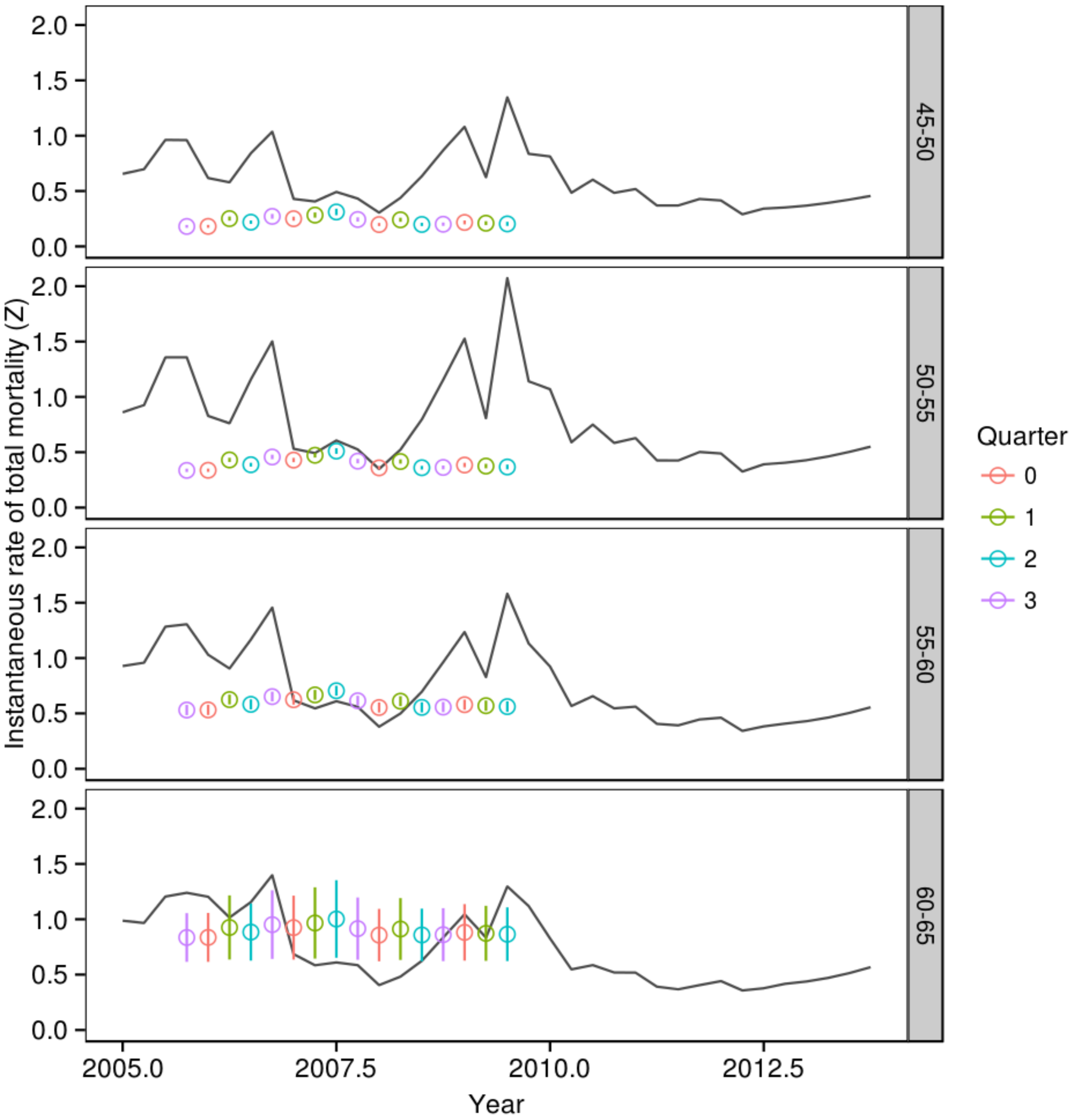


Figure 18: Observed (points) and expected (lines) western (W) purse seine (PS) tagging Z estimates. Error bars indicate +/- one standard error in estimates.

6.4 Size frequencies

6.4.1 Mean length by region, method, year and quarter

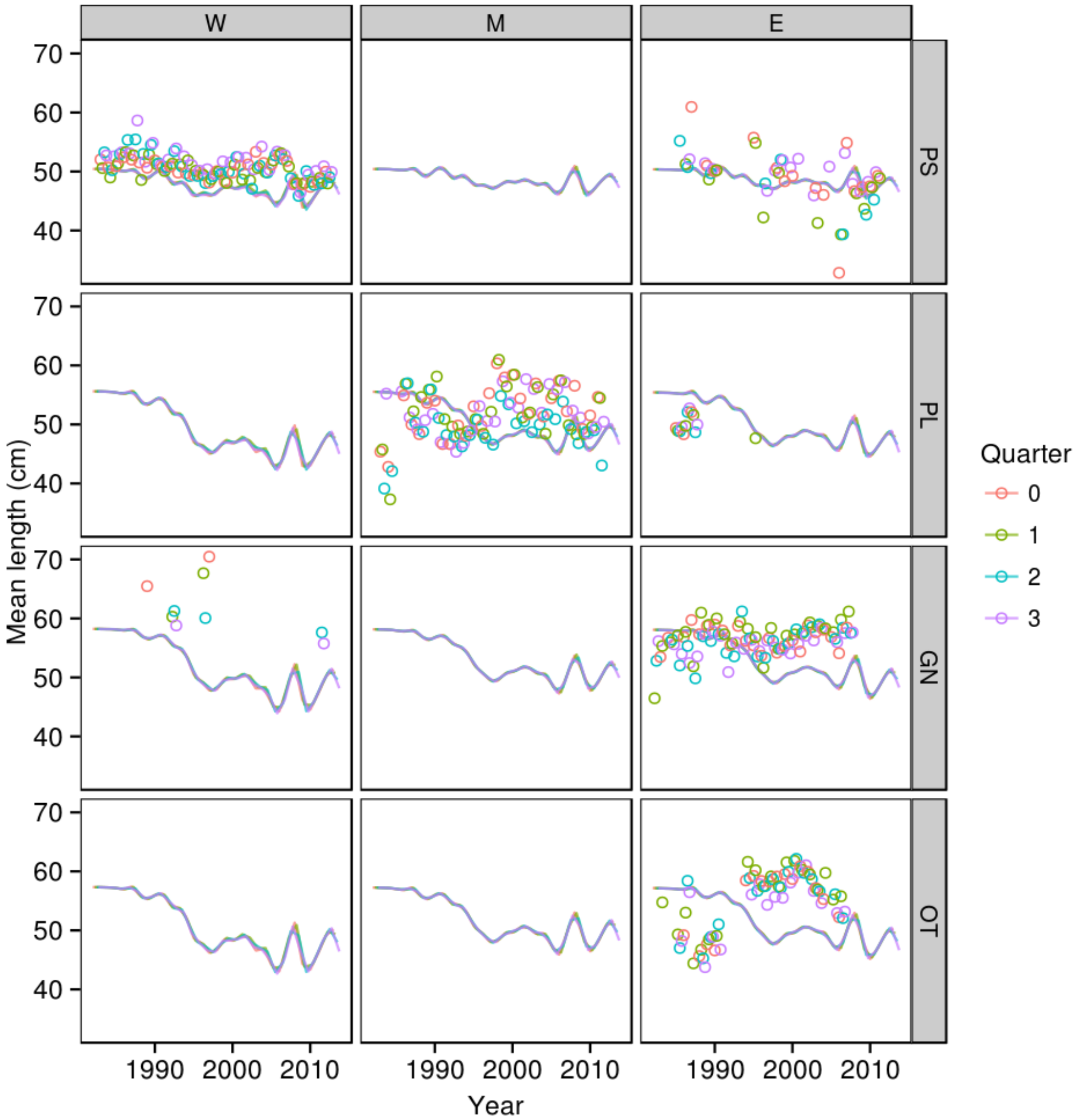


Figure 19: Observed (points) and expected (lines) mean length of catch by region, method, year and quarter.

6.4.2 By region, method & quarter (aggregated over years)

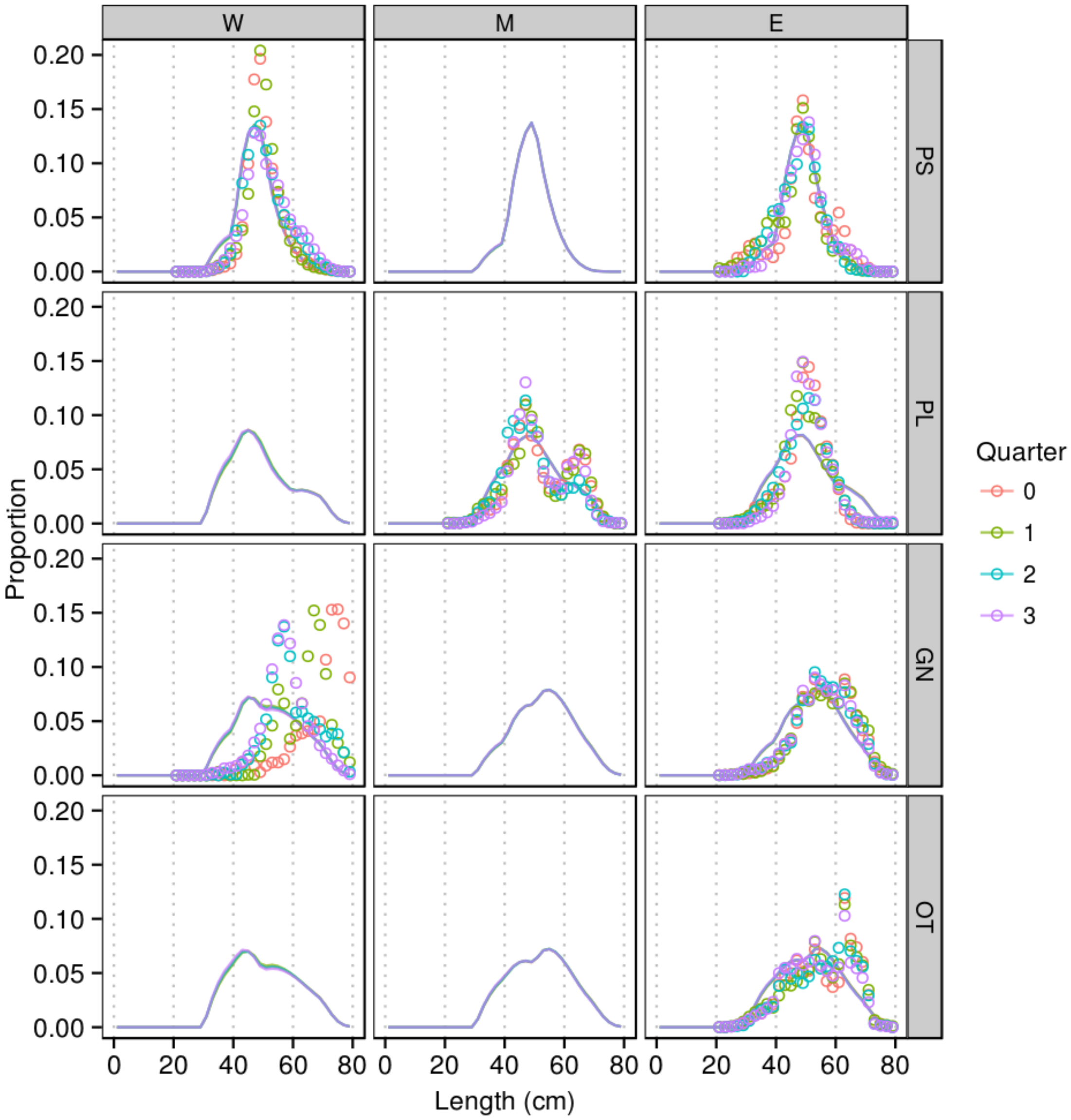


Figure 20: Observed (points) and expected (lines) proportion of catch in each length class by region, method & quarter (aggregated over years).

6.4.3 By year for a particular region & method (aggregated over quarters)

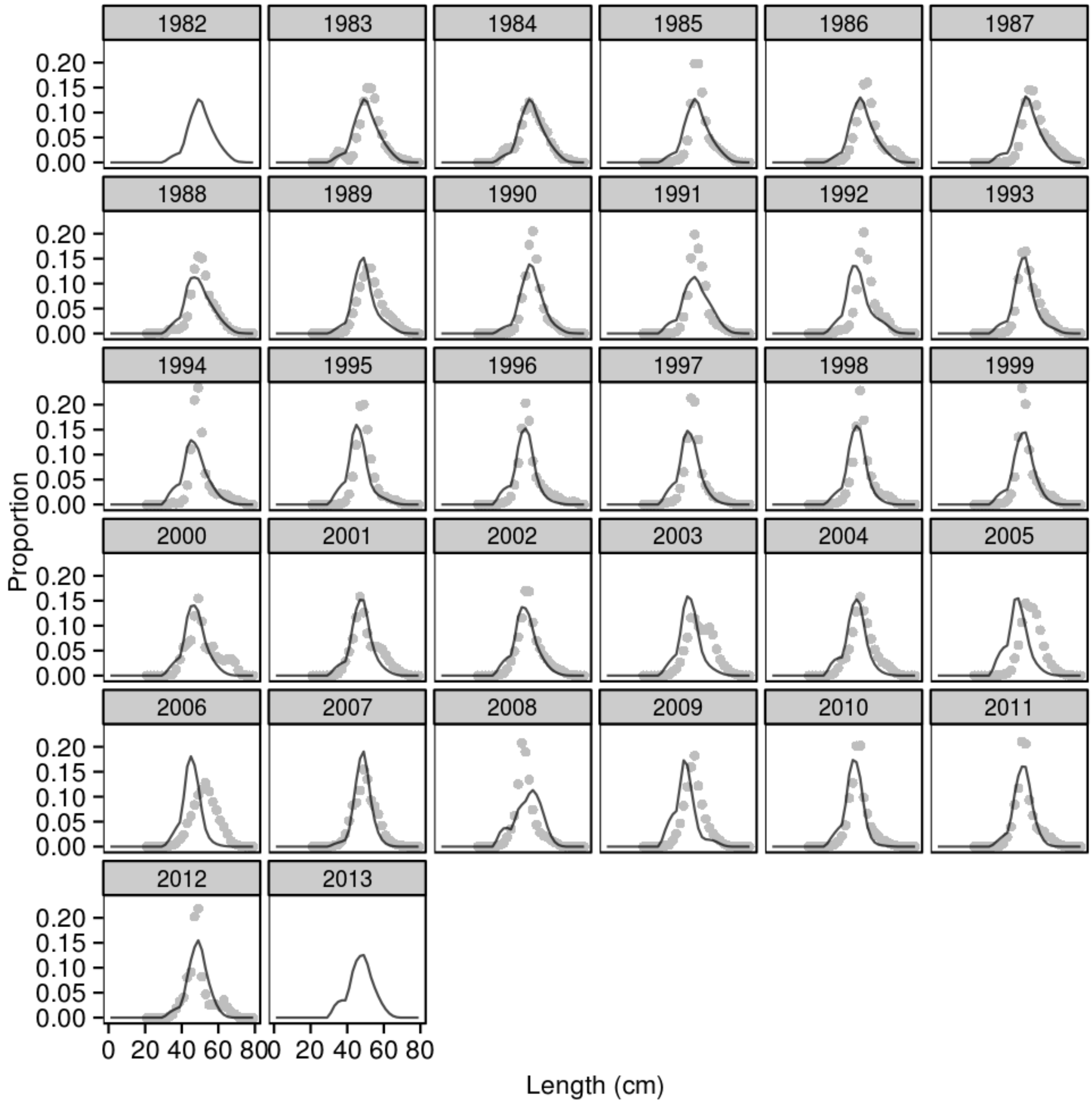


Figure 21: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

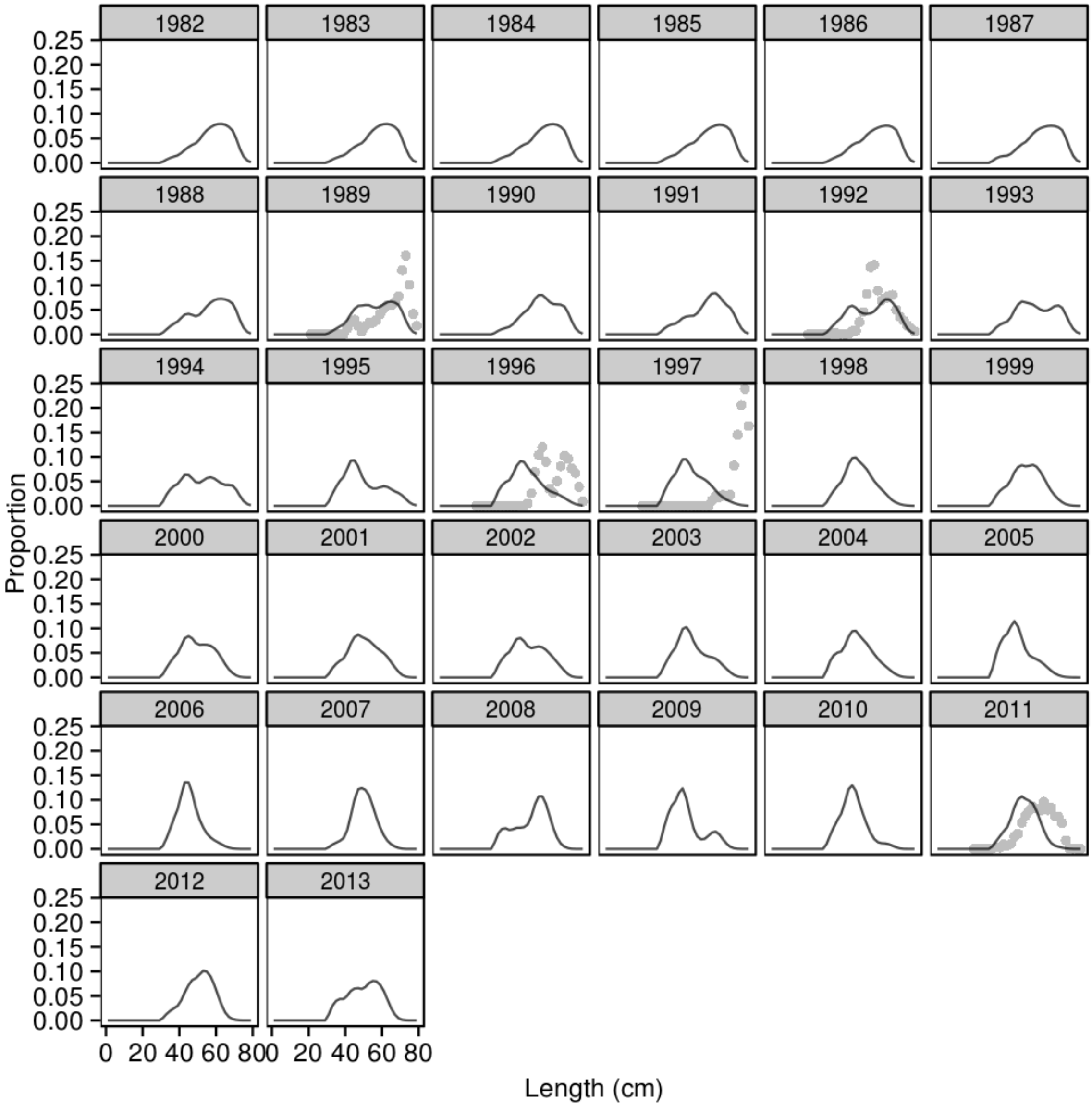


Figure 22: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

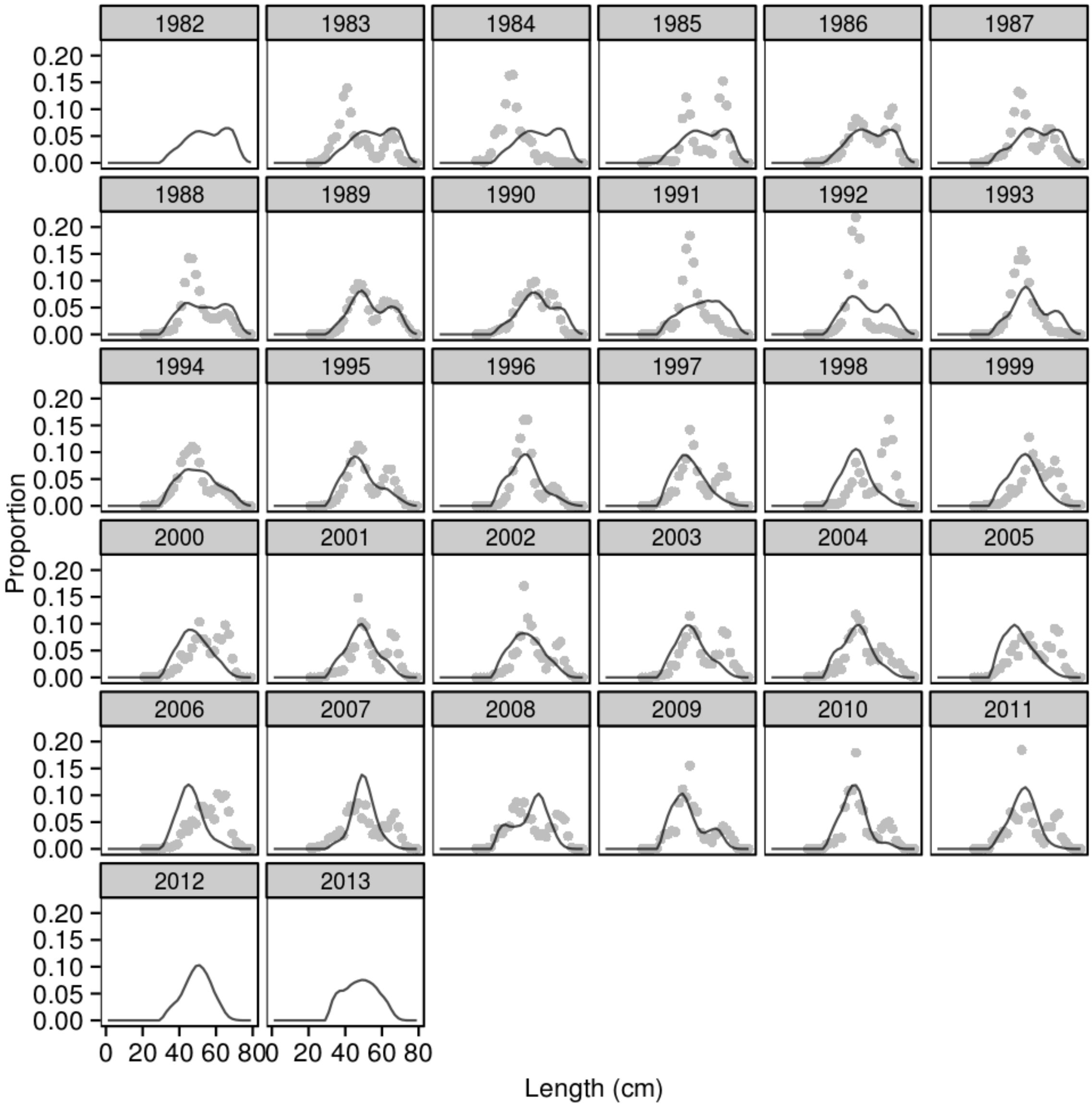


Figure 23: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

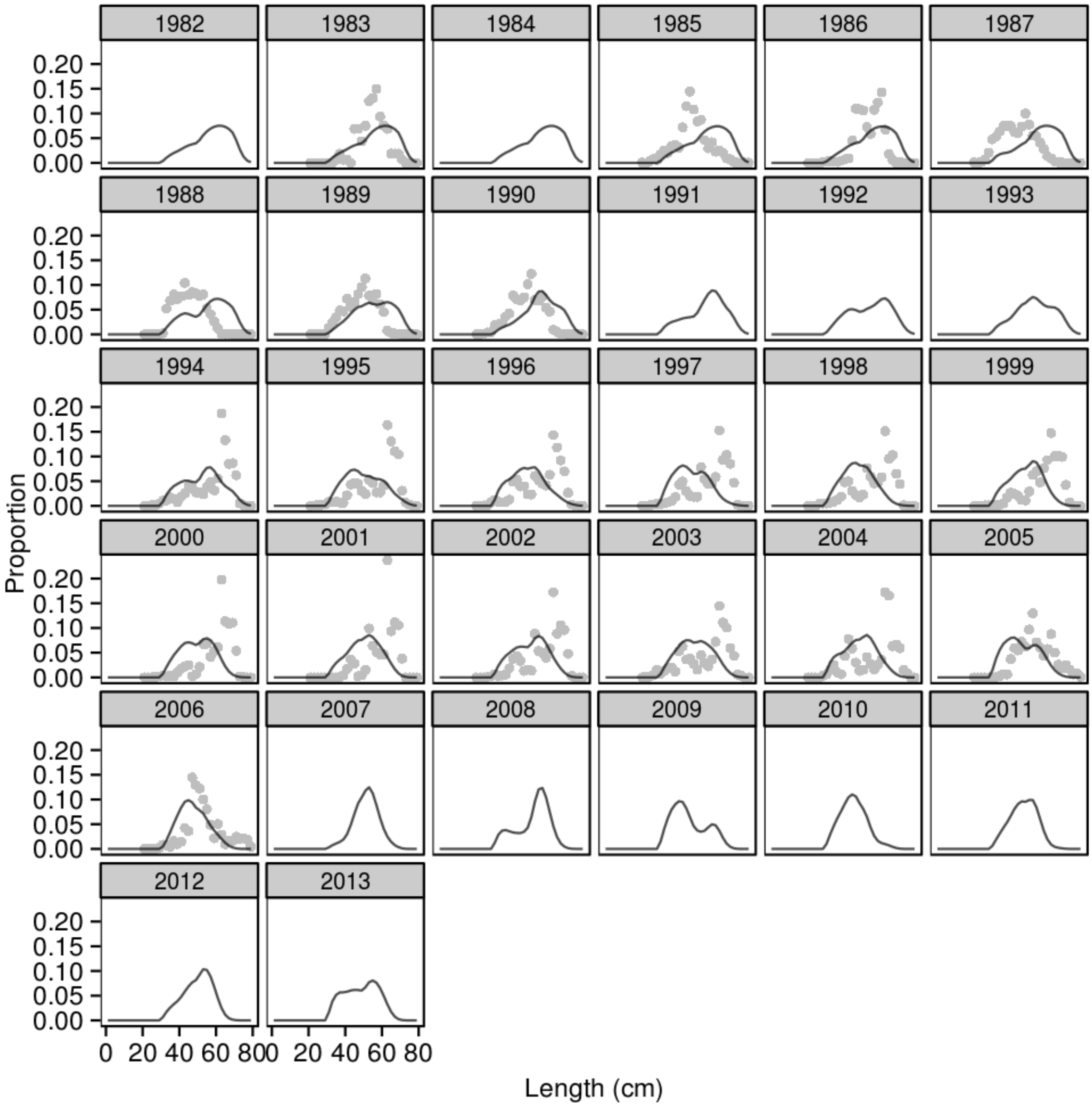
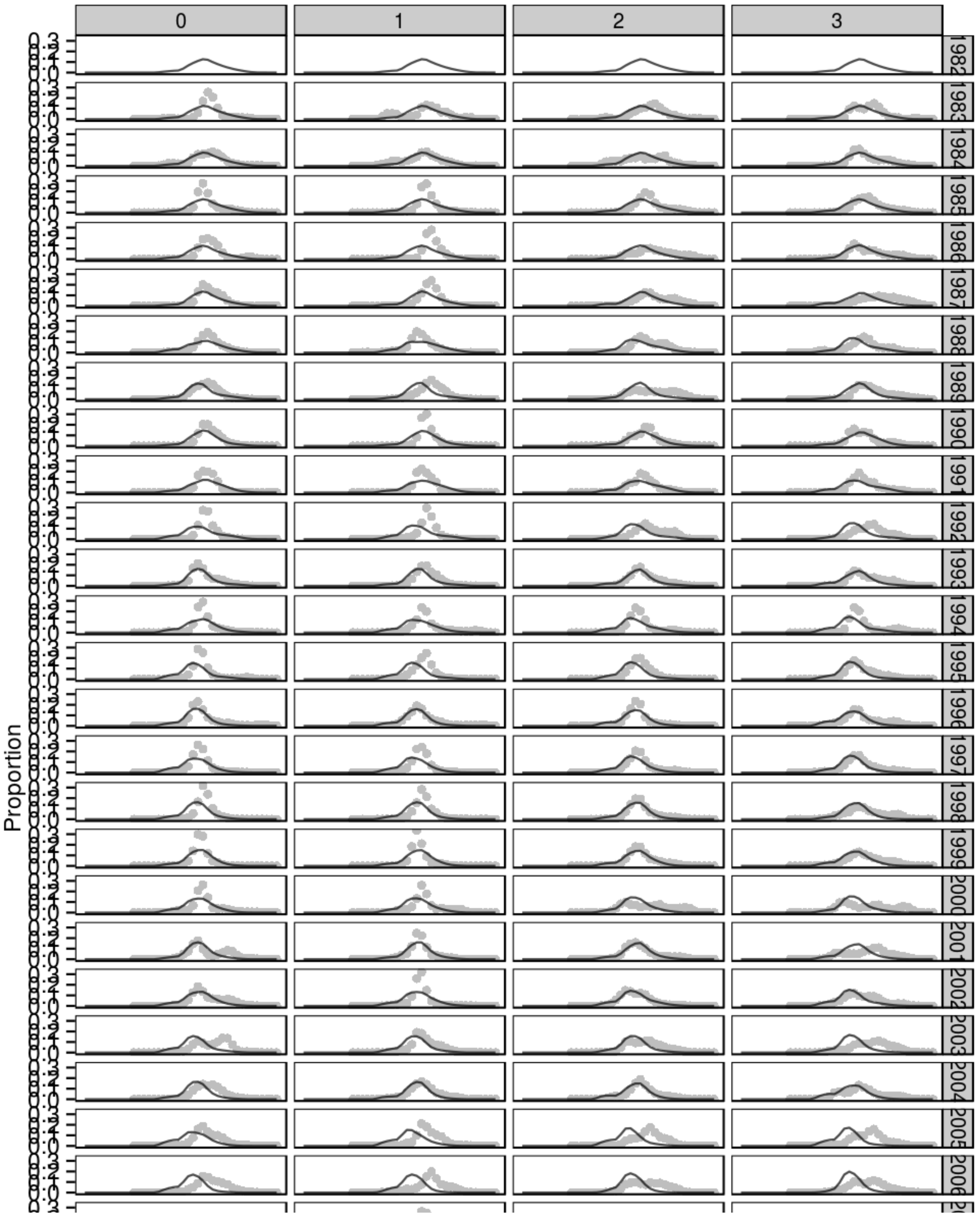


Figure 24: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

6.4.4 By year and quarter for a particular region & method (unaggregated)



0
1
2
3
Proportion
1982
1983
1984
1985
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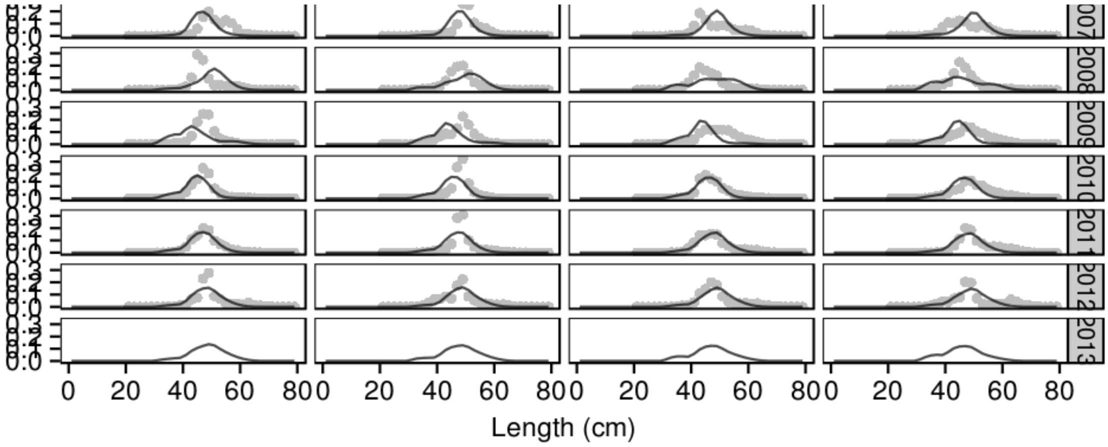

Figure 25: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

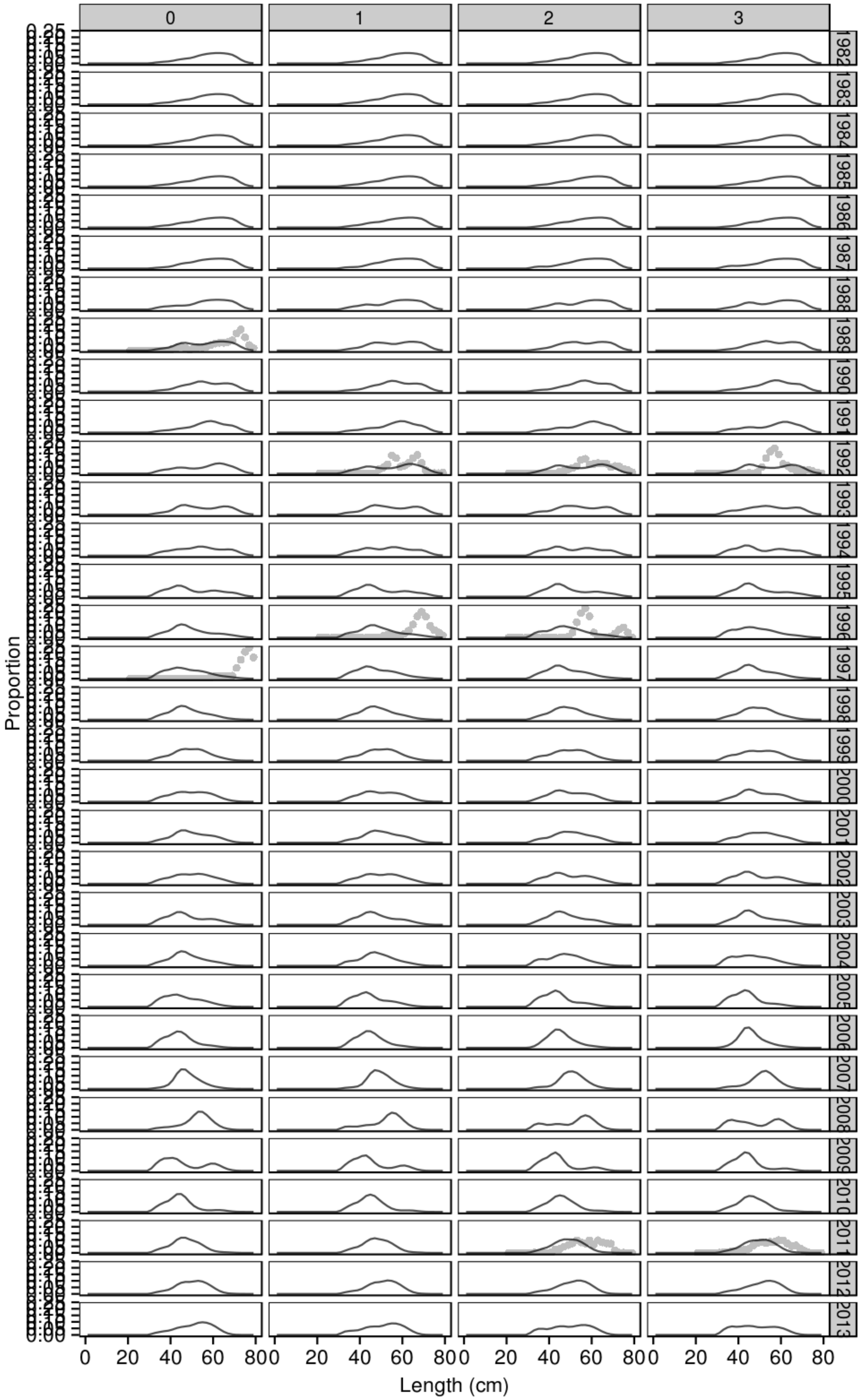

Figure 26: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

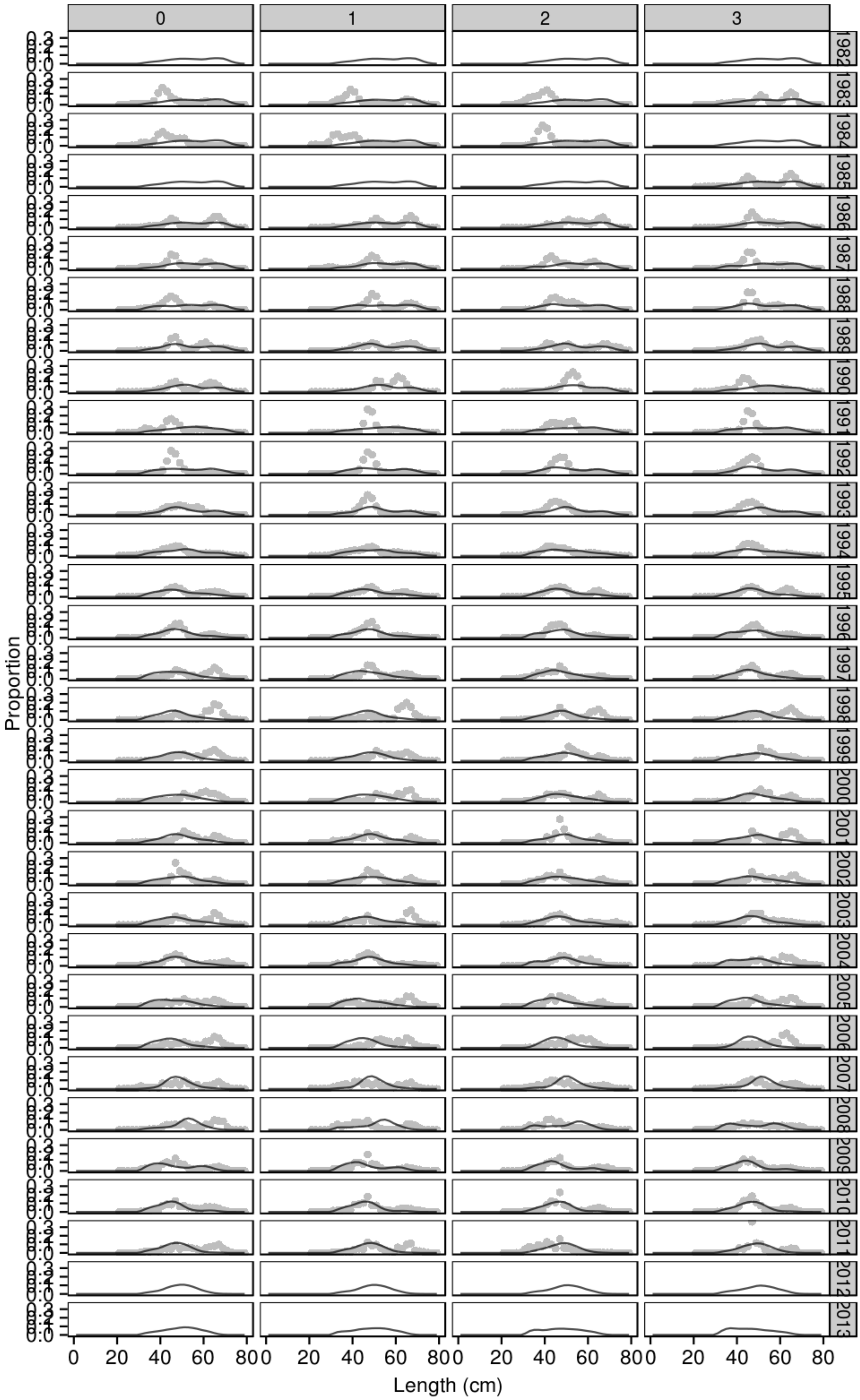

Figure 27: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

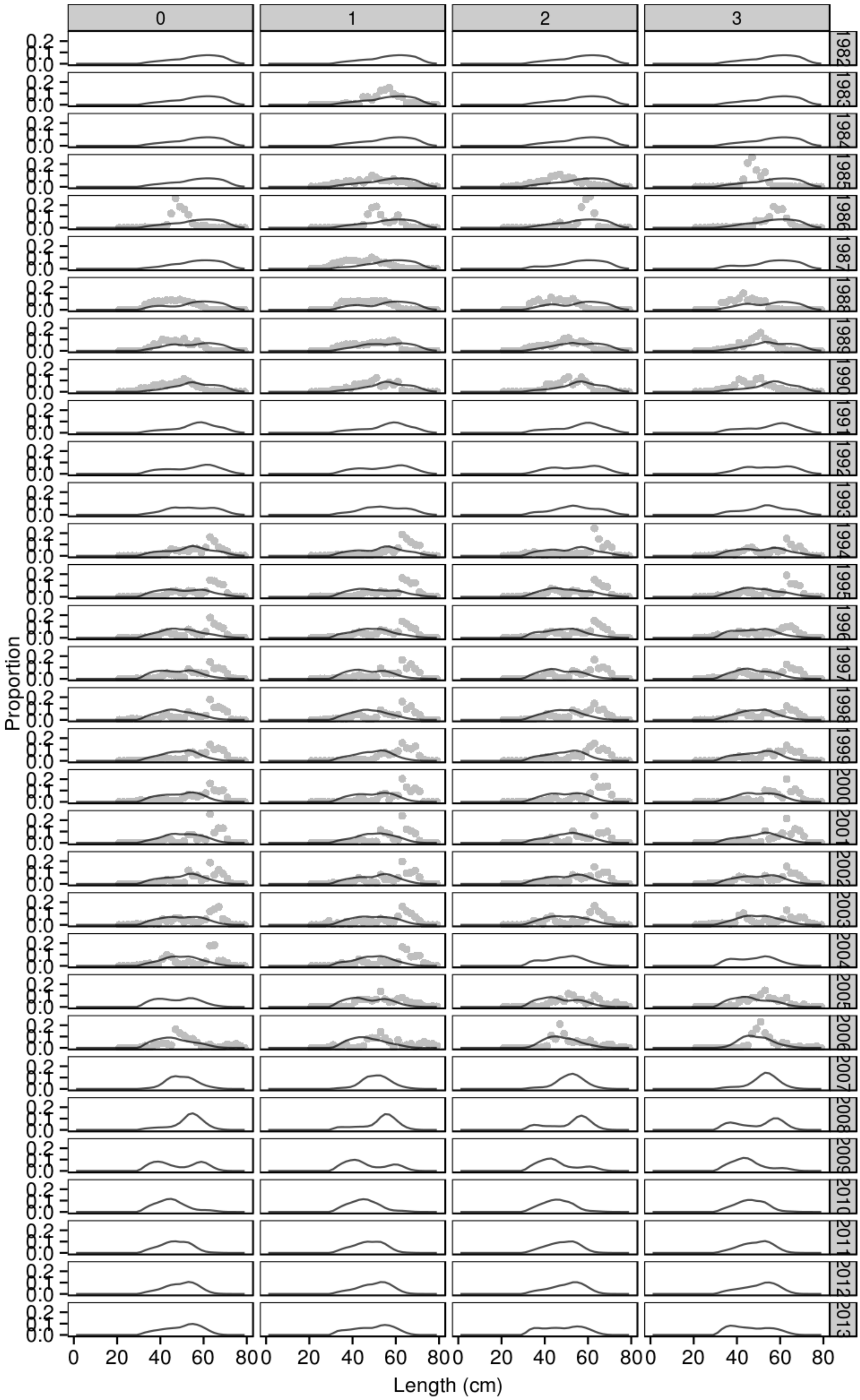

Figure 28: Observed (points) and expected (lines) size frequency distributions for span!text item$desc aggregated over quarters.

7 Yield curve and MSY estimation

7.1 Methods

The `ioskj.exe` executable has a `yield` task which generates outputs related to:

- the yield curve
- maximum sustainable yield (MSY)
- yield per recruit.

The yield curve is the equilibrium catch as a function of exploitation rate. This is generated by the model's `yield_curve` method which takes the model to deterministic equilibrium under a range of exploitation rates from 0 to 1. MSY is determined by the model's `msy_find` method which uses Brent's minimisation algorithm to find the exploitation rate which maximises yield.

In a simple biomass dynamics model the entire fish population is assumed to be selected by the fishery and thus the yield curve and MSY are a function of only the biological parameters. In the current model, yield is a function of the biological parameters, the fishery selectivity parameters and the distribution of fishing effort (i.e. relative exploitation rates) across fisheries (i.e. region/method subsets). If the shape of the selectivity curves or the relative exploitation rates of the fisheries changes then both MSY and the shape of the yield curve will change. Currently, the yield curve and MSY are calculated assuming that the specified exploitation rate applies to the three main fisheries in each region, western purse seine (W-PS), Maldive pole-and-line (M-PL) and eastern gillnet (E-GN). For all other fisheries, the exploitation rate is assumed to be 0.

The model's `yield_per_recruit` method calculates the numbers at age, mean length and weight at age from which a yield-per-recruit cureve can be derived.

All of these yield related outputs are dependent on the parameters used. The results presented in this section are based on the reference parameter set (read in from files in the `parameters/input` folder).

The results presented here should be considered preliminary. They are based on the reference parameter set only and ideally their sensitivity to alternative parameter values should be investigated. Also, further checking and testing of the model's equlbrium dynamics used for generating these results should be done. The main intention of this section is to promote discusssion regarding the pros and cons of alternative type of reference points (e.g. v based) for the Indian Ocean skipjack tuna fishery.

7.2 Overall yield curve and MSY

This section describes the overall yield curve and reference points related to maximising sustainable yield. Table 3 provides MSY related reference points and Table 4 provides reference points associated with alternative biomass levels. Figure 29 presents plots of various variables related to the yield curve.

Table 3: Yield curve related variables determined from the reference parameter set.

Symbol	Description	Value
	Exploitation rate which produces MSY (quarterly)	0.384
	Instantaneous rate of fishing mortality which produces MSY (quarterly)	0.485
	Maximum sustainable yield (quarterly)	84515.8
	Overall spawner biomass associated with maximum sustainable yield	493244
	as a percentage of pristine biomass	24.7
-	Number of iterations used to find MSY	8

Table 4: Exploitation rate, instantaneous fishing mortality rate, and equilibrium yield associated with alternative biomass levels. Note that for etc, values are approximate because they are taken from the yield curve generated from exploitation rates in increments of 0.05.

Biomass level	Exploitation rate (quarterly)	Fishing mortality rate (quarterly)	Yield (quarterly)	Yield/MSY		Effort/Effort at MSY
	0.384	0.485	84516	1	1	1
	0.3	0.082	83477	0.99	1.22	0.781
	0.2	0.053	77618	0.92	1.63	0.52
	0.15	0.039	70972	0.84	1.94	0.39

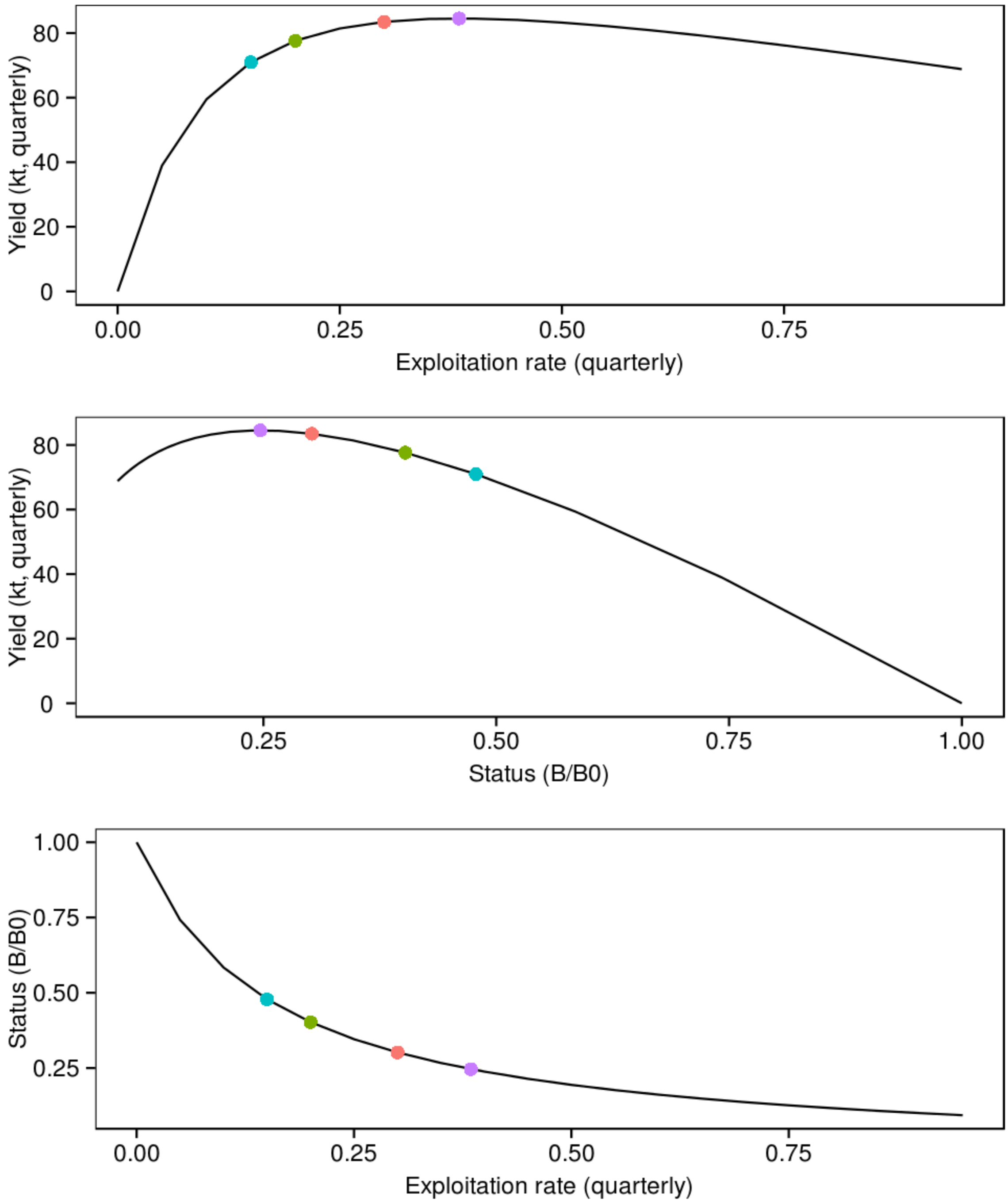

Figure 29: Relations between equilibrium yield, stock status and exploitation rate.(top) Equilibrium yield versus equilibrium exploitation rate. (middle) Equilibrium yield versus equilibrium stock status.(bottom) Equilibrium stock status versus equilibrium exploitation rate.

7.3 Fishery-specific yield curves

Each fishing method has a particular size selectivity (Figure 30) and as such, the yield curve for each fishery will differ in shape. In this section we examine the shape of the yield curve for the three main fisheries. Rather than using the biomass of spawners in these fishery-specific yield curves we use the fishery-specific vulnerable biomass. Vulnerable biomass is directly proportional to catch rates so is a better measure of how alternative exploitation rates may affect the economic performance of the fishery. Each fishery will have a difference vulnerable biomass because of the different selectivity curve.

For W-PS the yeild curve has its peak at high a much higher exploitation rate than for M-PL or E-GN (Figure 31 top). This occurs because the W-PS fishery is selecting for smaller fish. Note also that the vulnerable biomass of all three fisheries is similar at very low exploitation rates. As exploitation rates increase the numbers of older, larger fish decreases and as such the vulnerable biomass of both M-PL ad E-GN decreases (Figure 31 bottom).

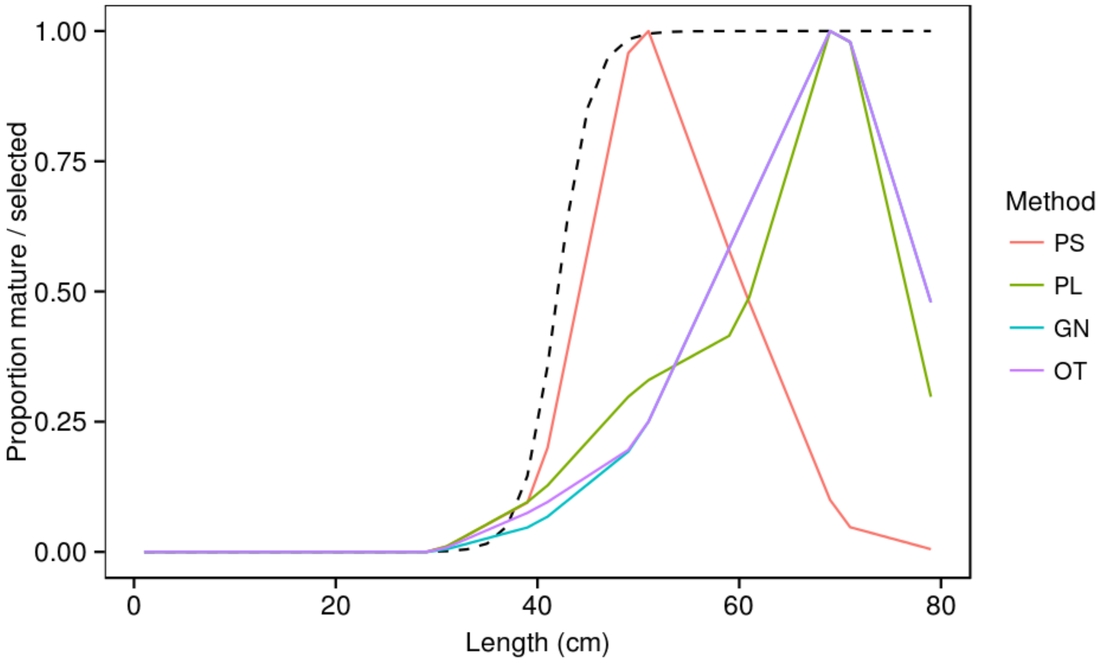

Figure 30: Maturity at length (dotted line) and selectivity at length (by method).

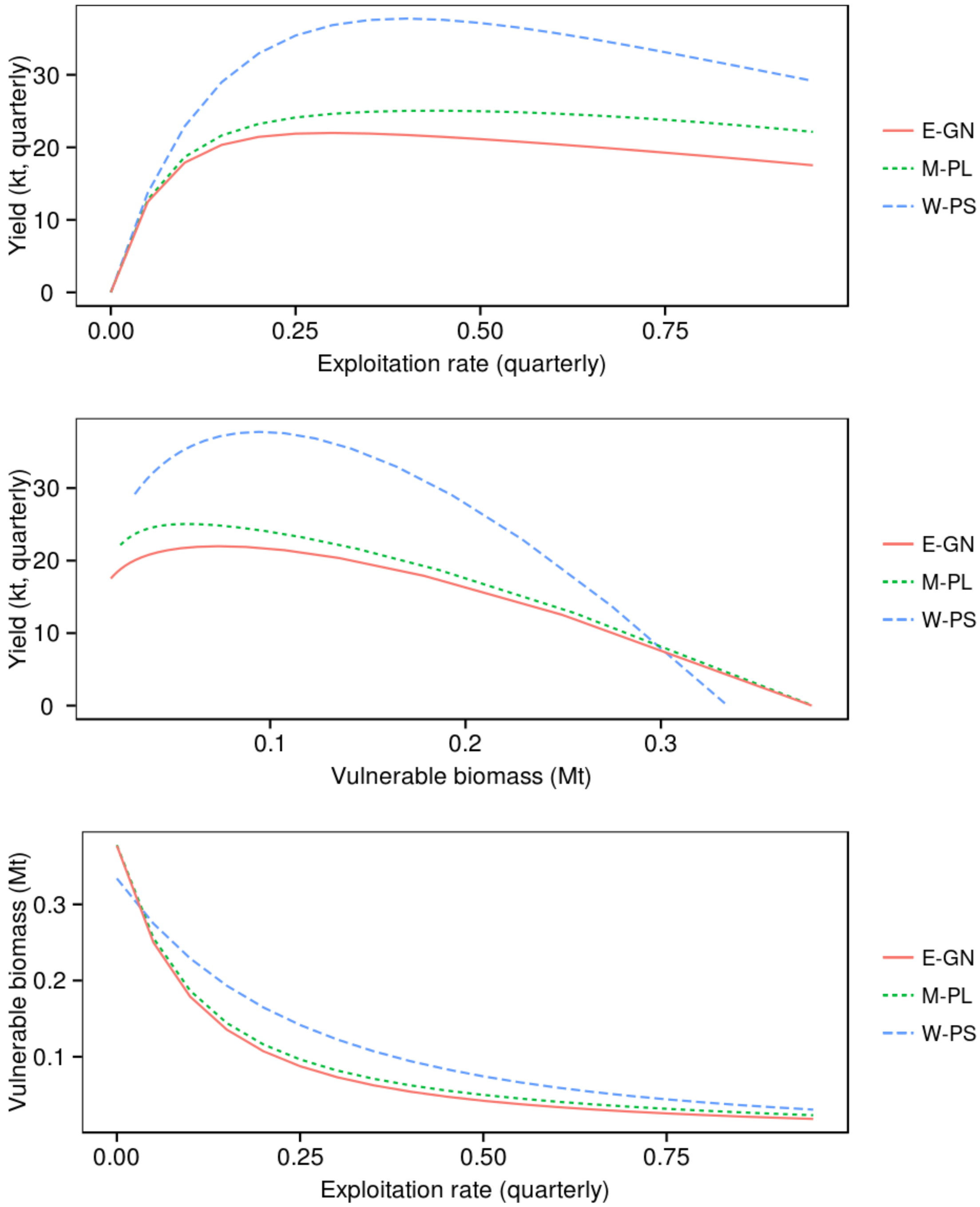

Figure 31: Fishery specific yield curves. Each panel provides a separate line for each fishery (region/method) given that the specified exploitation rate is jointly applied in each fishery.

7.4 Yield per recruit

To further investigate the nature of the yield in the fishery a simple yield per recruit analysis was done Figure 32. This suggests that yield per recruit is maximised at an age of 10 quarters (2.5 years) at a size of about 45cm. Note that this maximum will be highly dependent upon the growth curve and the mortality curve both of which are highly uncertain for fish below 45cm. As such, this analysis should be considered ancillary and treated with caution.

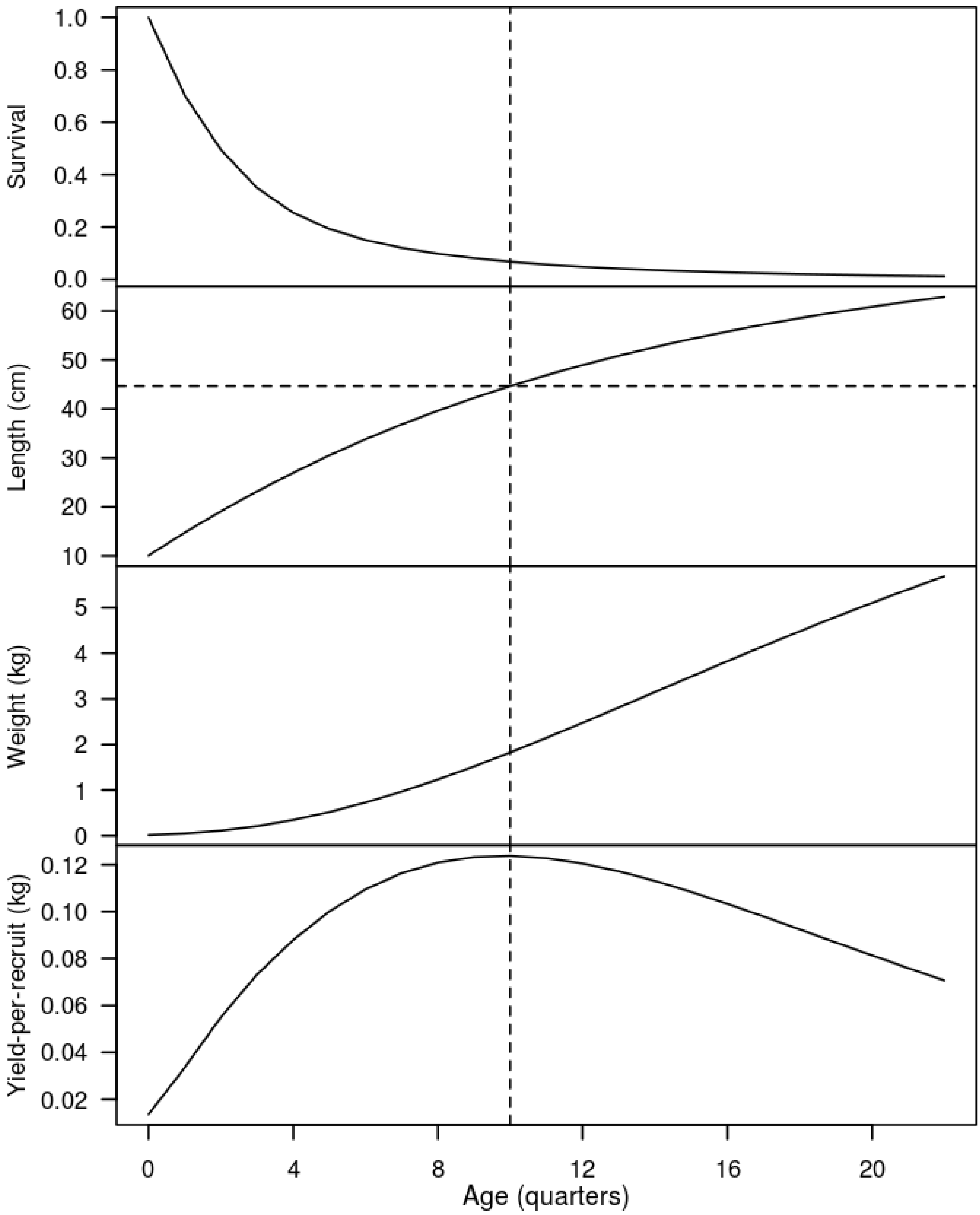

Figure 32: Yield per recruit analysis.

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