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Management strategy evaluation for the Indian Ocean skipjack tuna fishery

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Abstract

This report describes progress towards management strategy evaluation (MSE) for the Indian Ocean skipjack fishery. This work has been progressed by the Maldives pole-and-line fishery in partial fulfilment of the conditions of its Marine Stewardship Council (MSC) certification. Adam et al (2013) provided a background and rationale for the project. An operating model (OM) has been developed which partitions the skipjack population by 3 regions, 24 quarterly ages, and 40 two cm size bins and the fishery by 3 regions and 4 gear types (purse seine, pole-and-line, gill net, others). Currently the operating model is conditioned using parameter estimates from the 2014 stock assessment. Three contrasting classes of management procedure (MP) have been implemented: BRule (a generic harvest control rule based on an estimate of stock status), FRange (a MP which adjusts effort when fishing mortality is outside a target range) and IRate (a MP which recommends a total allowable catch using a CPUE-based biomass index). Each MP is evaluated over a twenty five year period against performance statistics that include average annual yield, variability in catch, CPUE for the main region/gear combinations , average stock status and probability of stock status falling to low levels.

Introduction

Substantial progress has been made on coding and testing the operating model and management procedures. A MSE workshop of WPM in Ispra, Italy during March 2014 was updated on progress and feedback was obtained (IOTC 2014). An Advisory Committee (AC) has been established for the project. The AC includes a number of experienced MSE practitioners and tuna fisheries scientists including those involved in both the IOTC WPTT and WPM. The AC met in October 2014 to review progress and made a number of important suggestions and recommendations for the work (ISSF 2014). Several of those recommendations were incorporated in time for WPTT16. As far as possible, recommendations arising from WPTT16 have been incorporated prior to WPM5 (5-6 December 2014).

All the code and documentation for the operating model (OM) and management procedures (MPs) are available in a source code management repository hosted on the IOTC WPM account at:

https://github.com/iotcwpm/SKJ

MSE usually proceeds as an iterative process with successive refinements to both operating models and candidate management procedures and repeated evaluations towards selection of final management procedure (e.g.Kolody et al 2008). The primary intention of presenting this paper is to solicit suggestions on current methodology, in particular the model structure, assumptions and parameterisation.

This document provides an overview of aspects of the operating model and its conditioning as well as candidate management procedures and their evaluation. Consistent with an iterative approach to MSE, much of the project documentation has been established using templates that can automatically refreshed based on model outputs. The most recent versions of those documents are available via the above URL. For some, current versions (at time of writing) are also appended to this document as appendices.

Model structure

Overview

The operating model (OM) uses a quarterly time step and is currently set up for conditioning to data for the period 1950-2014 and for evaluation of candidate management procedures for the period 2015-2039 (25 years, 100 quarters).

The OM is spatially structure into three regions:

- Western (W)
- Maldives (M)
- Eastern (E)

Four fishing methods are distinguished:

- Purse seine (PS)
- Pole and line (PL)
- Gillnet (GN)
- Other (OT)

The fish population is structured by partitioning by region, age (quarters 0-23) and size (2cm length bins, 0-80cm). The principal advantage of partitioning by size is to allow for proper modelling of size-based selectivity. However, it also allows for modelling of other potentially size based processes in the future.

Spawning and recruitment

A proportion of mature fish spawn in each season with parameters based on the work on Grande (2013). A Beverton-Holt stock recruitment relationship based on total, pooled spawning biomass across all three regions is assumed. The resulting recruits are distributed to each region according to a parameter which describes the proportion of recruits to that region.

Natural mortality

The instantaneous rate of natural mortality at size s is modelled as a function of weight at sizes (Lorenzen 1996). To prevent M going to very high levels at small sizes, M is restricted to be a maximum of the mortality at a length of 21cm.

Growth

Growth is described using a size transition matrix which is calculated based on the von Bertallanfy growth function. Variation in growth is modelled as a normal distribution with a constant standard deviationand a coefficient of variationon the increment.

Movement

The proportion of fish moving between regions in one quarter is described by the movement matrix defined by six off-diagonal parameters.

Selectivity

There is a separate selectivity curve for each method (i.e. PS, PL, GN, OT) which is assumed to be the same in the three regions. Selectivity is modelled using a piecewise spline with knots at 20, 30, 40, 50, 60, 70, and 80cm.

See the appendix "**Indian Ocean skipjack model : Model description**" for further model details including equations. See "**Indian Ocean skipjack model :General outputs**" for a display of model variables.

Model parameterisation and conditioning

Work has been done on establishing prior probability distributions for model parameters based on the available literature (see http://iotcwpm.github.io/SKJ/parameters/description/). These priors have been used for preliminary model conditioning using the FST algorithm (Bentley and Langley 2012, see http://iotcwpm.github.io/SKJ/feasible/display/). Although this approach to model conditioning may be pursued further at a later stage, the project's Advisory Committee recommended that the 2014 assessment grid be used as the basis for model conditioning in the short term.

The 2014 stock assessment is based on a grid of model runs encompassing some of the major model uncertainties. Code has been added for extracting parameter estimates from Stock Synthesis III output from each of the grid runs (see https://github.com/iotcwpm/SKJ/tree/master/ss3). Currently, the following parameters are been taken from each of 72 grid runs:

- Natural mortality (a grid variable)
- Stock-recruitment steepness (a grid variable)
- Unfished spawning biomass (B_0)
- Recruitment deviations, 1985-2010
- Selectivity for each fishing method at 20, 30, 40, 50, 60, 70, and 80cm.

The OM assumes a relationship between weight and natural mortality whereas most of the assessment grid runs assume a constant mortality rate across sizes. In these cases, the M estimated by the stock assessment is assumed to apply to fish of 1kg weight with the M of fish of other sizes assumed to follow the Lorenzen form. An alternative would be to assume no weight to mortality relationship for these particular grid runs.

The current stock assessment model has a single area whereas the OM has three regions. Consequently there are several important parameters which are not available from the 2014 assessment:

- The proportion of overall recruitment going to each region, χ_r
- The parameters of the movement matrix e.g. $\omega_{ma,we}$

In these cases we are currently using a wide range of parameter values and examining the sensitivity of results. For example, the robustness of management procedures could be tested against contrasting scenarios in which there is little or no movement (i.e. approximating three discrete regional stocks) or there are high movement rates (i.e. approximating a single stock).

Management procedures

Several classes of candidate management procedure (MP) will be considered in this study. Those classes are mainly intended to illustrate the wide variety of possible MPs: the data inputs they use, their algorithmic form and the management controls which they alter (e.g. effort versus catch). Currently, three classes of management procedure have, or are being, implemented,

- BRule: a generic harvest control rule which defines a recommended fishing mortality based on a target fishing mortality and limit and threshold biomass reference points
- FRange: estimates fishing mortality (F) at certain time intervals (e.g. 5 years) and recommends increases or decreases in effort depending on whether F falls within, below or above a target range.
- IRate: uses a smoothed CPUE index as an index of abundance and recommends a total allowable catch based on that index and some proportion of the historical exploitation rate.

Suggestions for additional classes of MP are welcomed. See the appendix "**Indian Ocean skipjack model: Description of management procedures**" for further model details of each class of management procedure.

Next steps

Two reports describing the work to date will be presented to WPM5: (1) Description of operating model structure, assumptions and conditioning (2) Candidate management procedures and evaluation results.

References

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Grande, M (2013). The reproductive biology, condition and feeding ecology of the skipjack, Katsuwonuspelamis, in the Western Indian Ocean PhD Thesis. Department of Zoology and Animal Cell Biology, Universidad delPais Vasco.

IOTC (2014) Report of the 3rd IOTC WPM small working group on Management Strategy Evaluation.IOTC-2014-WPTmT05-INF03.http://www.iotc.org/documents/report-3rd-iotc-wpm-small-working-group-management-strategy-evaluation

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Indian Ocean skipjack model : Model description

DRAFT

This documentation is a draft under active development. As such, it may not exactly mirror what is in the current version of the code. Separate documentation, generated from the model's C++ source code, is also available .

Introduction

This document describes a simulation model for the skipjack fishery in the Indian Ocean. The model has been designed for use in simulation based evaluation of alternative management strategies for the fishery. This document outlines the structure of the model, describes prior probability distributions for model parameters, model conditioning algorithms and conditioning results.

The model, and consequently this document, are under development. The general approach to model development has been to start simple and add complexity as required. Potential alternative model formulations are noted throughout the document.

The following convention is used for assigning symbols for the model: 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 but 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.

Dimensions

Several dimensions are used to partition aspects of the model (e.g. fish numbers, catches).

Time

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).

Region

There are three regions (r), West (we), Maldives (ma) and East (ea). The term "region" is used in preference to "area" because using the latter would confound the a subscript which is also used for age.

Age

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. $0, 1, 2, ..., 23$

Size

Fish size (s) is represented in forty, 2cm bins, $0-2, 2-4, ..., 78-80cm$.

Method

Five fishing methods (m) are defined (Table 1).

Table 1 : Symbols used for model dimensions

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

Fish

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 G is the growth transition matrix, D is the natural survival rate, E is the exploitation rate, and M is the movement transition matrix.

Length

The length of fish of size s is the midpoint of the bin size,

$$L_s = 2s+1$$

Weight

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

$$W_s = \alpha(L_s)^{\beta}$$

Parameters of the length-weight relationship could vary by region i.e. α_r, β_r

Maturity

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

$$O_s = \frac{1}{1 + \underset{\upsilon}{19^{\tau - L_s}}}$$

Maturity could be a function of age, rather than size, i.e. O_a , and/or vary by region e.g. τ_r

Spawning

The proportion of mature fish that spawn in each quarter is allowed to vary according to a model parameter, ρ_q .

Recruitment

Recruitment occurs in each quarter and is partitioned by region and size, $R_{r,s}$. The total number of recruits is based on the total spawning biomass in the previous quarter,

$$S = \sum_{r \in \{we,ma,ea\}, a=0 \ldots \vec{a}, s=0 \ldots \vec{s}} N_{r,a,s} O_s W_s \rho_q$$

where O_s is the proportion of fish that are mature at size s , W_s is the weight of fish at size s , and ρ_q is the proportion of fish that spawn in quarter q .

The total spawning biomass is used as the basis for determining a recruitment over all three regions, $\overline{R}$ based on the Beverton-Holt stock recruitment function,

$$\overline{R} = 4\eta\theta \frac{S}{(5\eta - 1)S + \dot{S}(1 - \eta)} D_t$$

where η is steepness, θ and $\dot{S}$ are the respectively the recruitment and spawning biomass in the absence of fishing, and D_t is the recruitment deviation at time t which is lognormally distributed with mean of 1 and standard deviation of σ .

To do : add in recruitment autocorrelation

This total recruitment is distributed across the three regions,

$$R_{r,s} = \overline{R} \cdot \chi_r \cdot A_s$$

where χ_r is the proportion of recruits which recruit into region r and A_s is the proportion of recruits of size s which is based on a normal distribution with mean, μ and standard deviation ζ ,

$$A_s = \frac{1}{\sqrt{2\pi\zeta^2}} e^{-\left(\left(L_s - \mu\right)^2\right)/2\zeta^2}$$

Currently, recruitment is pooled across all areas. This could be changed via a recruitment dispersal matrix.

Natural mortality

The instantaneous rate of natural mortality at size s is modelled as a function of weight at size s,

$$M_s = \nu W_s^{\gamma}$$

To prevent M_s going to very high levels at low s, M_s is restricted to be a maximum of M_{10} (i.e. the mortality at a length of 21cm). The survival rate in one quarter is thus,

$$D_s = e^{-0.25 M_s}$$

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,

$$I_s = (\lambda - L_s)\left(1 - e^{-0.25\kappa}\right)$$

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

$$J_s = \sqrt{\zeta^2 + \left(\phi I_s\right)^2}$$

The proportion of fish growing from size $\dot{s}$ to size s in one quarter is thus,

$$G_{\dot{s},s} = \int_{l=2s}^{l=2(s+1)} \frac{1}{\sqrt{2\pi} J_{\dot{s}}} \frac{e^{-\left(L_{\dot{s}} + I_{\dot{s}} - l\right)^2}}{2\left(J_{\dot{s}}\right)^2}$$

Growth could vary by region and/or time e.g λ_r, κ_t

An alternative to the vonB model would be to use the two-stanza growth model and parameter estimates of Everson et al (2012).

Movement

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

$$M_{\dot{r},r} = \begin{bmatrix} 1 - \omega_{ea,ma} - \omega_{ea,we} & \omega_{ea,ma} & \omega_{ea,we} \\ \omega_{ma,ea} & 1 - \omega_{ma,ea} - \omega_{ma,we} & \omega_{ma,we} \\ \omega_{we,ea} & \omega_{we,ma} & 1 - \omega_{we,ea} - \omega_{we,ma} \end{bmatrix}$$

There could be separate movement parameters for each age (or size) e.g. $\omega_{ma,we,a}$, or more simply, the relative proportion of fish moving could vary by age (or size).

Fishing

Exploitation rate

The biomass that is vulnerable to each method, m in each region r, is calculated by summing over ages and sizes,

$$V_{r,m} = \sum_{a=0,\ldots,\vec{a},s=0,\ldots,\vec{s}} N_{r,a,s} W_s P_{m,s}$$

where $P_{m,s}$ is the relative selectivity of method m for fish of size, s.

Determine best way to parameterize selectivity ogives e.g. logistic, splines etc.

The exploitation rate in region r of method m is then,

$$E_{r,m} = \frac{C_{r,m}}{V_{r,m}}$$

Indian Ocean skipjack model : general outputs

DRAFT

This documentation is a draft under active development. As such, it may not exactly mirror what is in the current version of the code. Separate documentation, generated from the model's C++ source code, is also available .

Introduction

This document displays model outputs generated from the `run` task (i.e. `./ioskj.exe run`) which uses the default parameter values (those marked `#value`) defined in `parameters/input/parameters.cila` . Since those values are user inputs the following may not reflect best parameter estimates. This is primarily intended for checking and illustrating the model.

Recruits

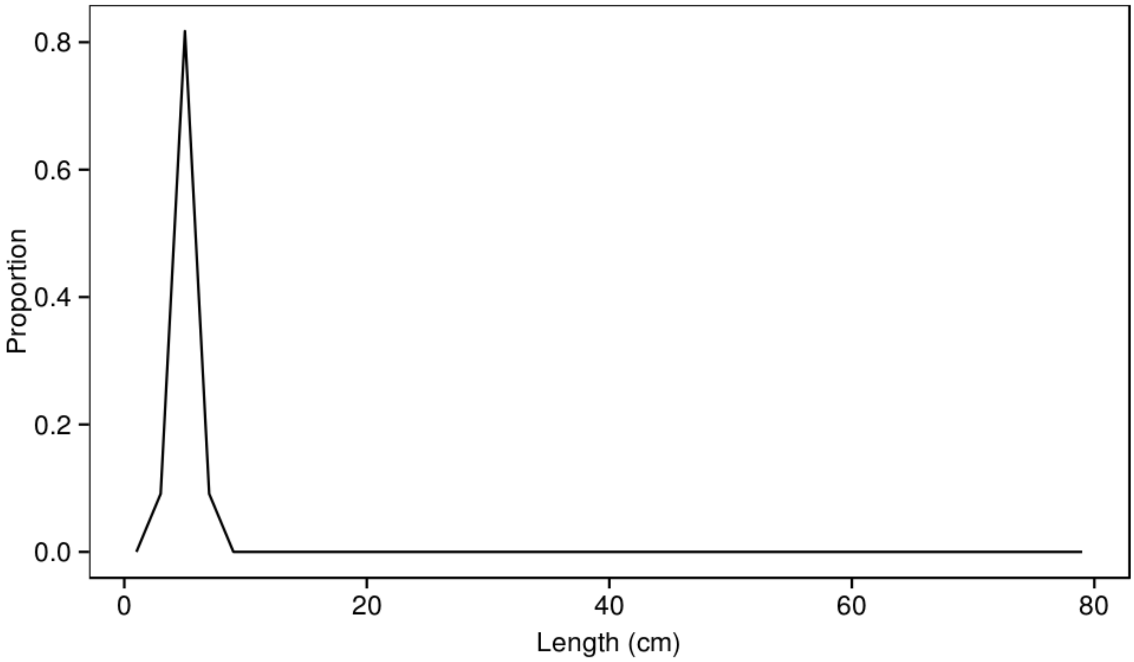


Figure 1 : Distribution of the length of recruits. Recruits are added to the model following this distribution.

Growth

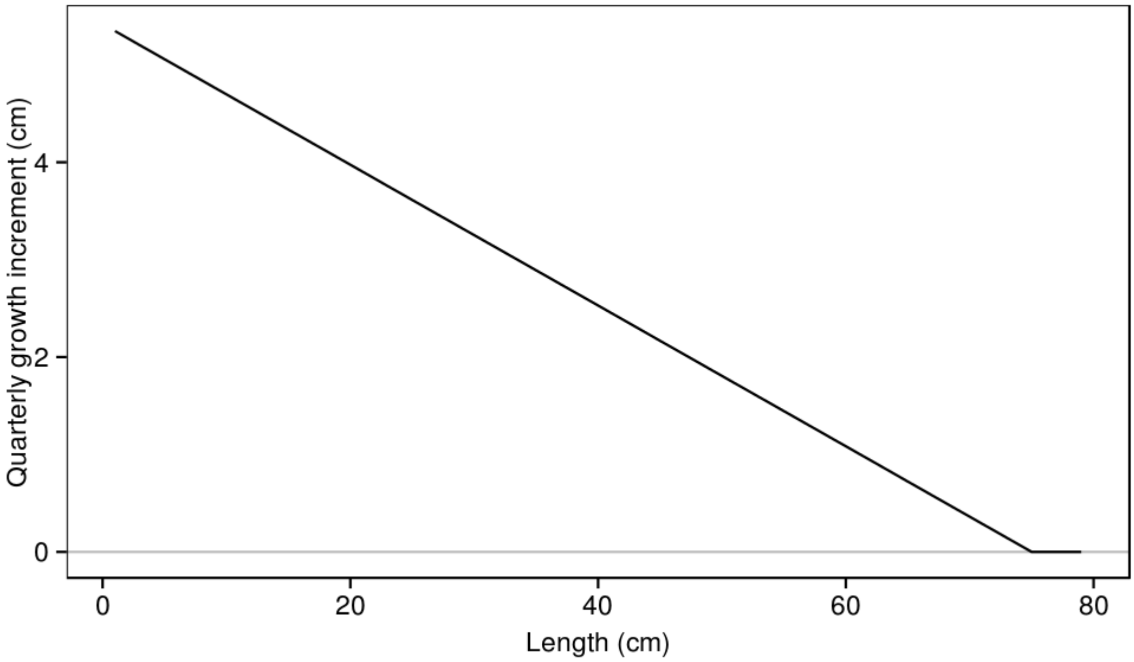


Figure 2 : Growth increments by length.

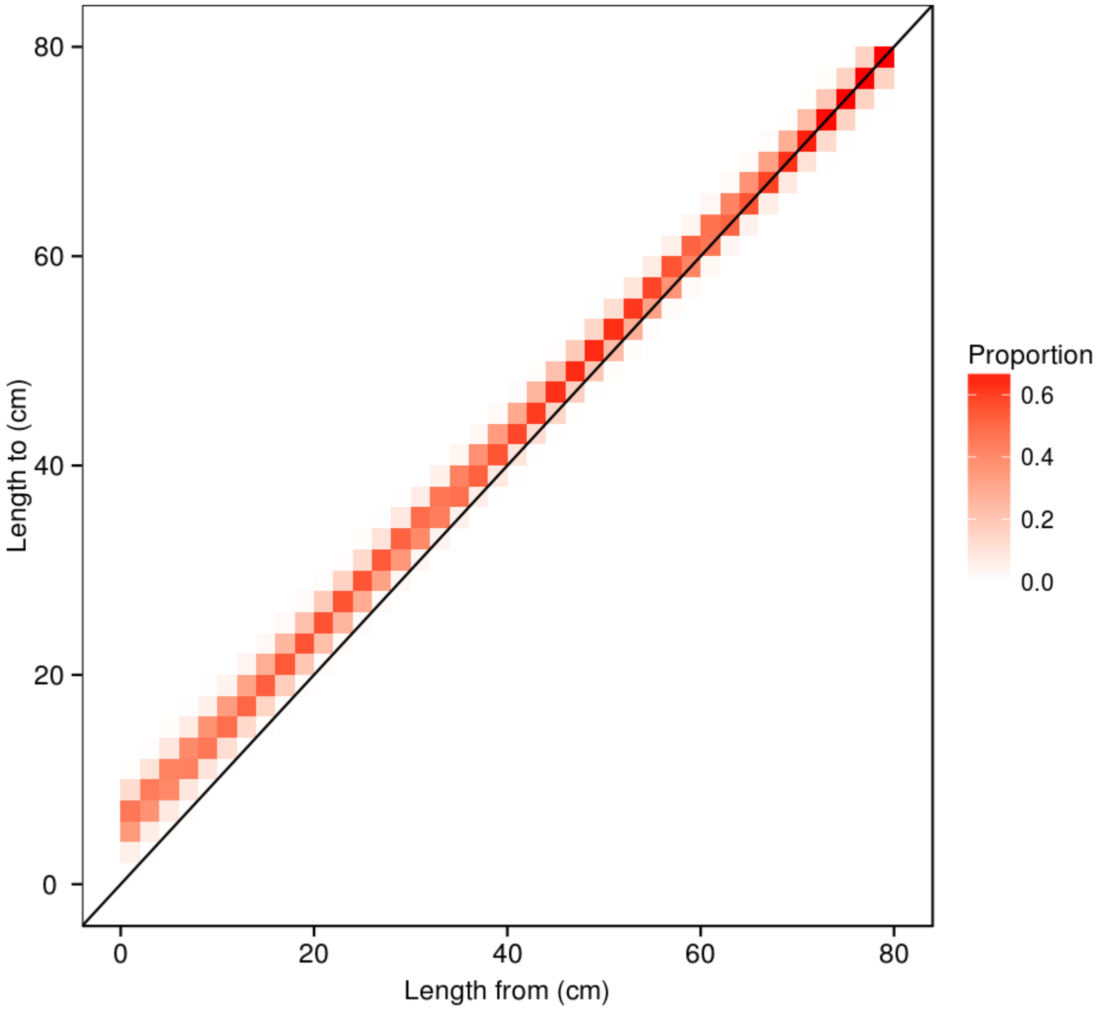


Figure 3 : Growth transition matrix indicating the proportion of fish that transition from one length class to other length classes in one quarter.

Weight

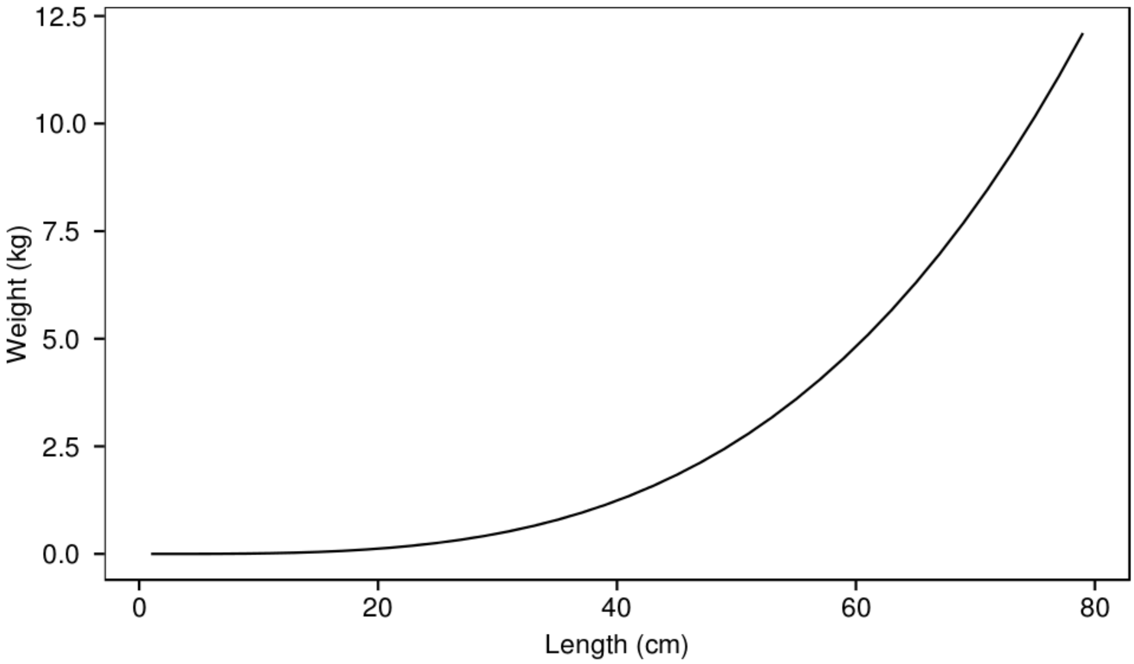


Figure 4 : Weight at length.

Maturity

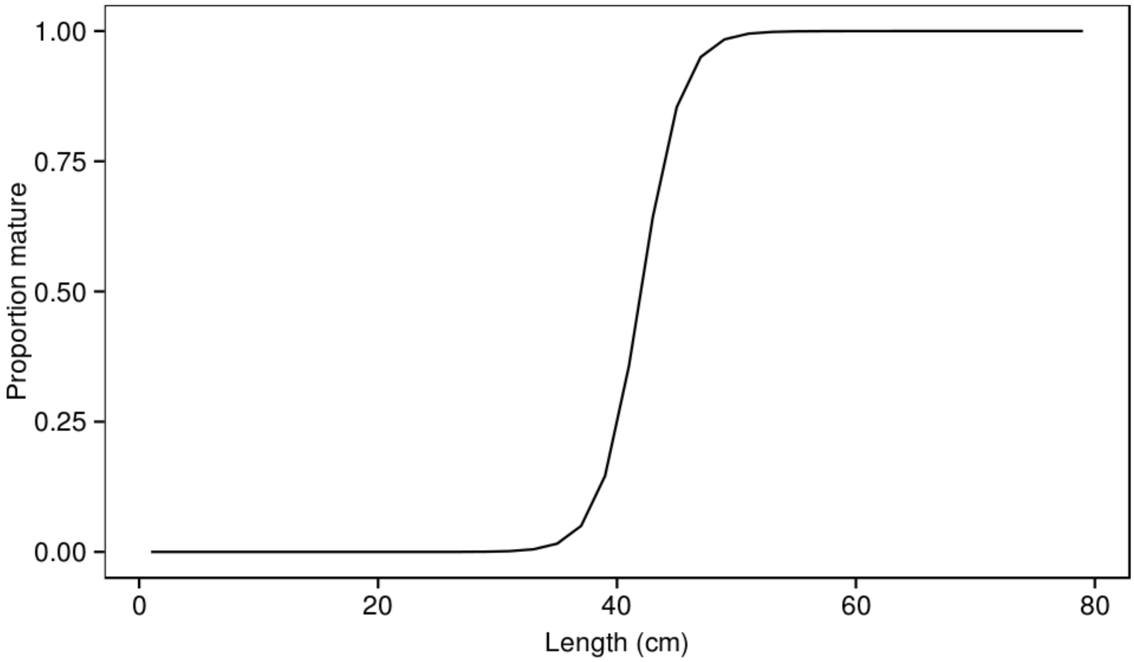


Figure 5 : Maturity at length

Mortality

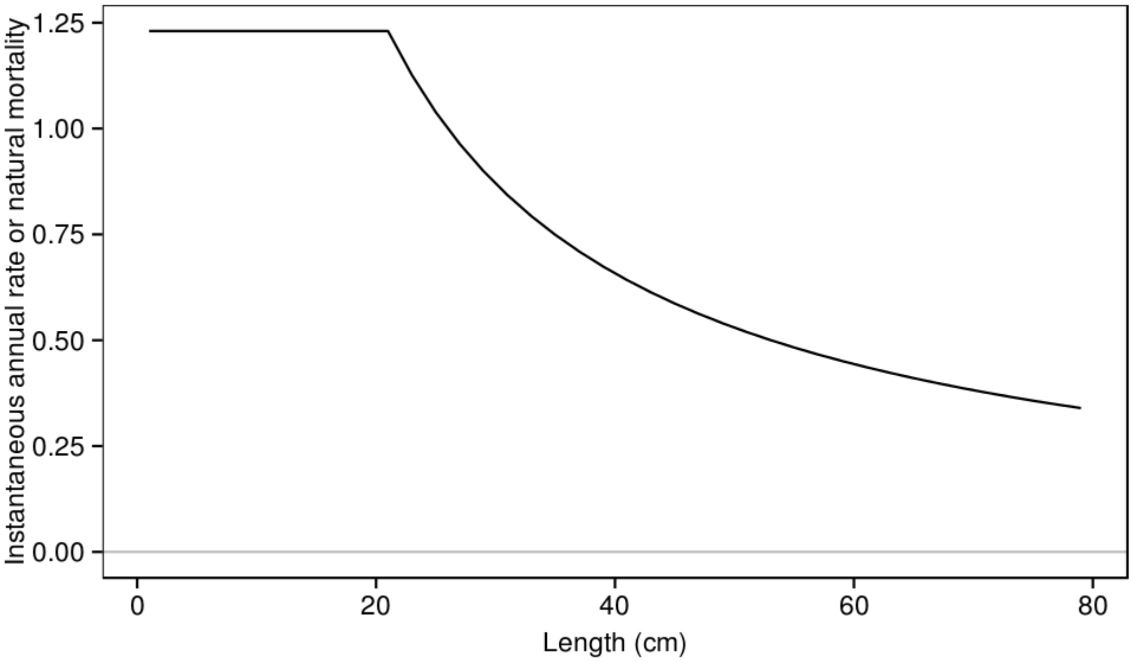


Figure 6 : Mortality at length

Movement

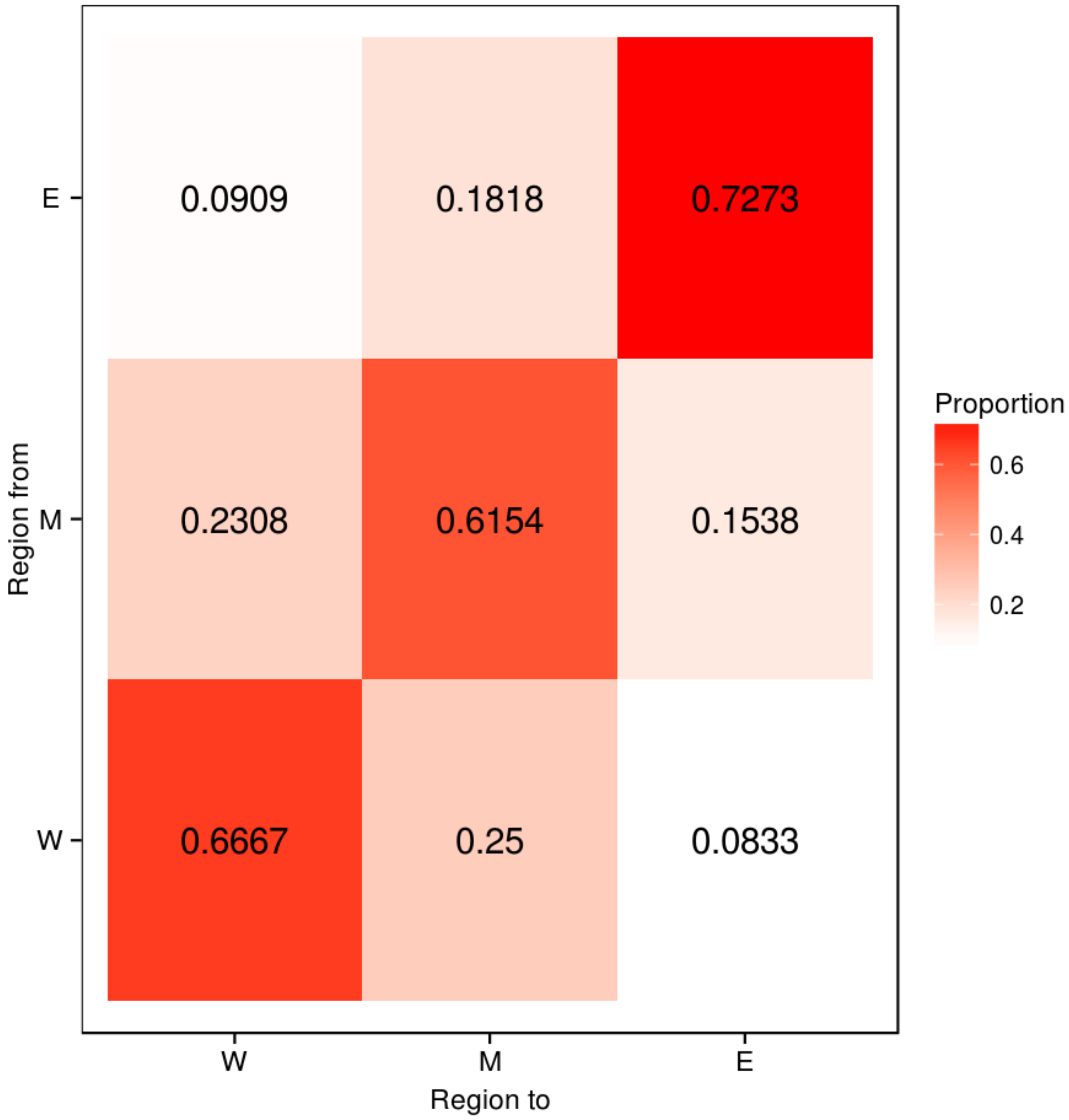


Figure 7 : Movement proportion by quarter. Each cell indicates the proportion of fish moving from one region to another in one quarter.

Unfished equilbrium state

The following figures show the distributions of lengths in the population in an unfished state.

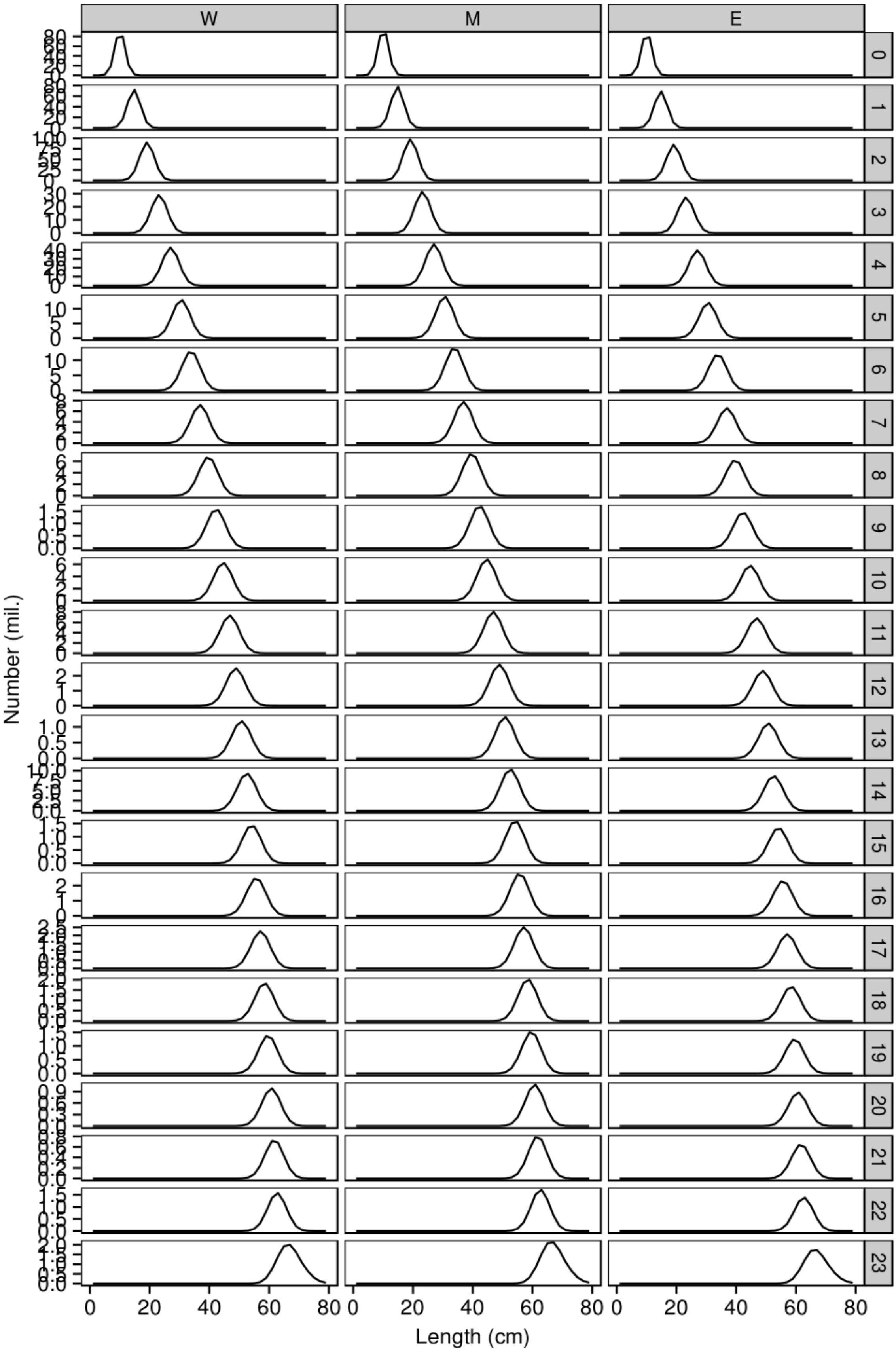


Figure 8 : Unfished equilbrium numbers at age and size and region. Each panel shows the length ditribution for a particular age (in quarters) and region.

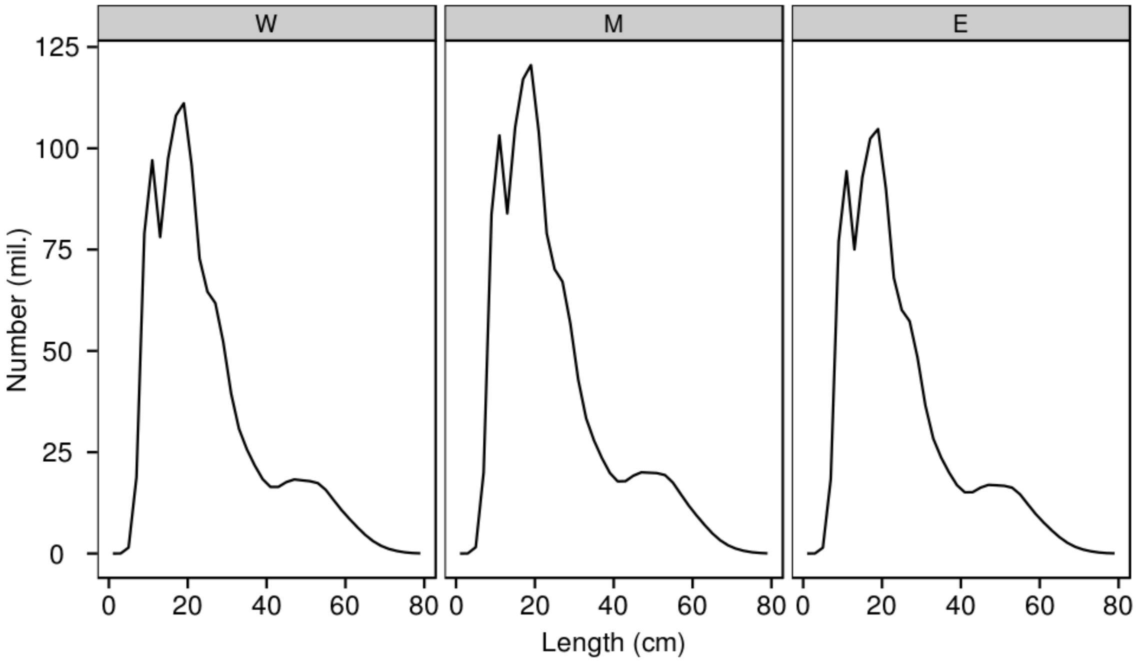


Figure 9 : Unfished equilibrium numbers at size by region. Each panel is the aggregated length distribtuion across all ages within a particular region.

Selectivities

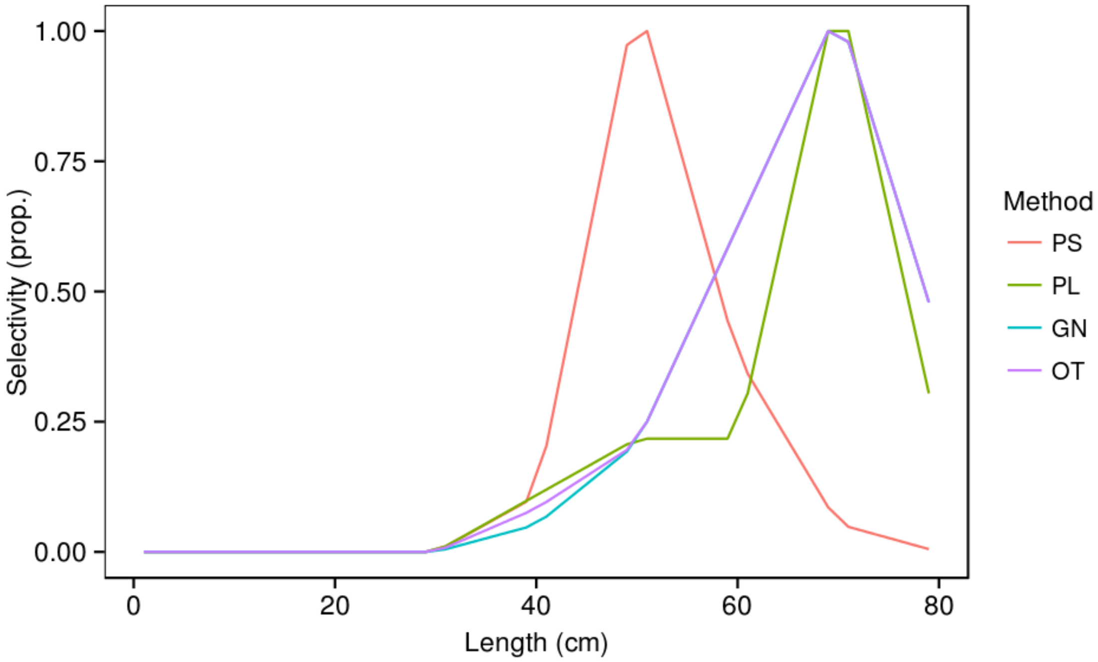
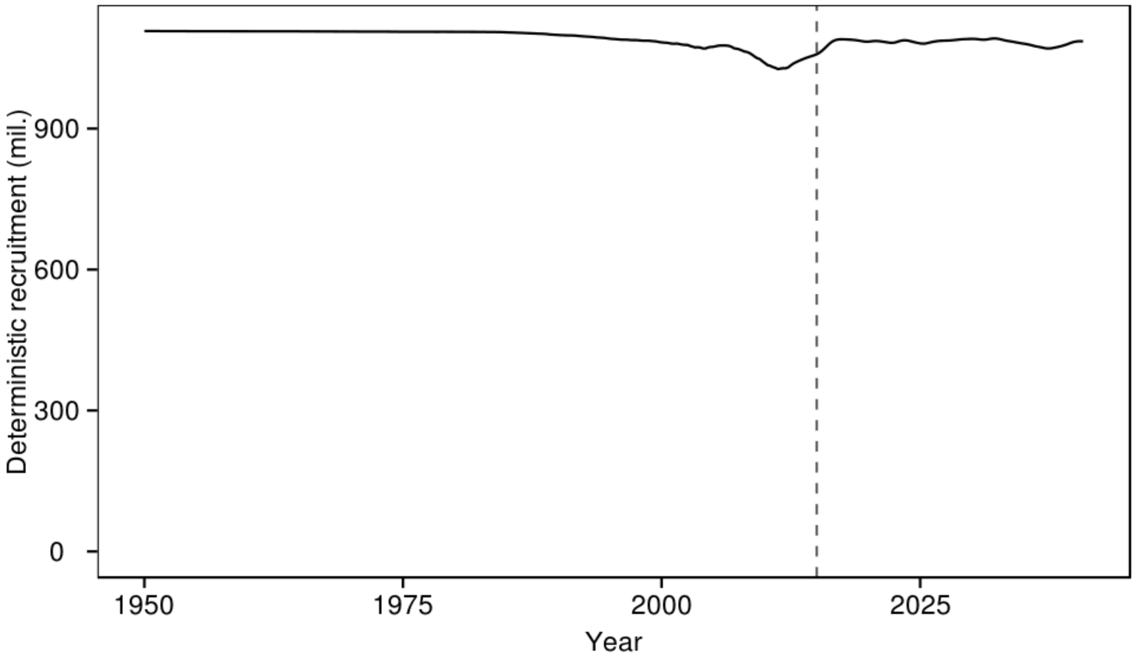
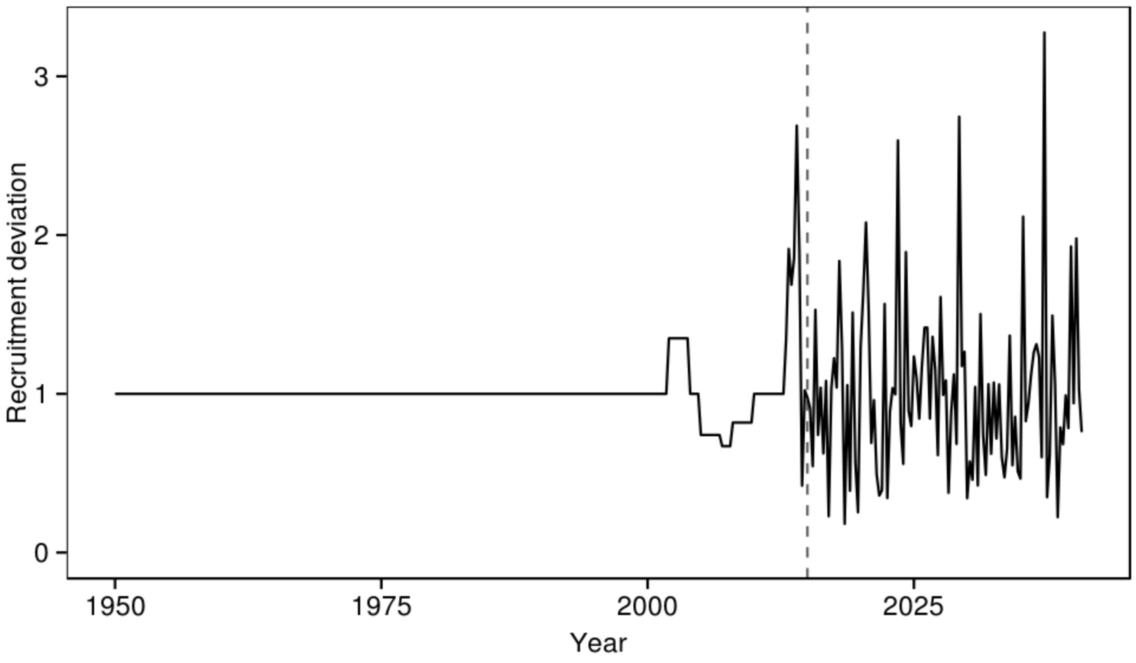


Figure 10 : Selectivity at length by fishing method.

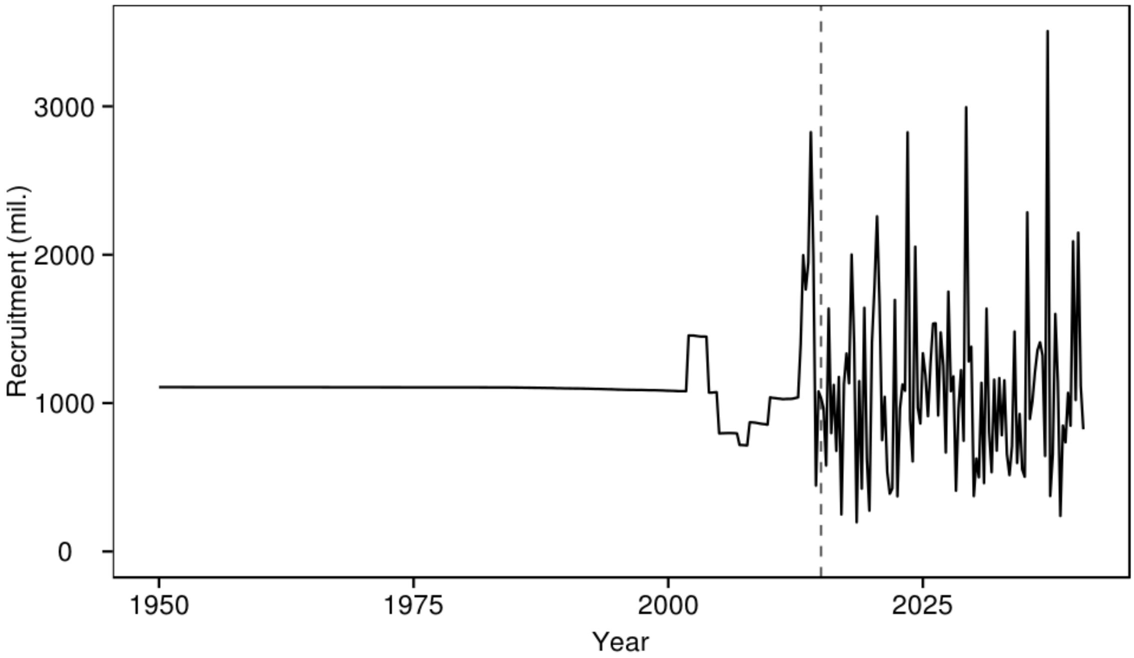
Recruitment



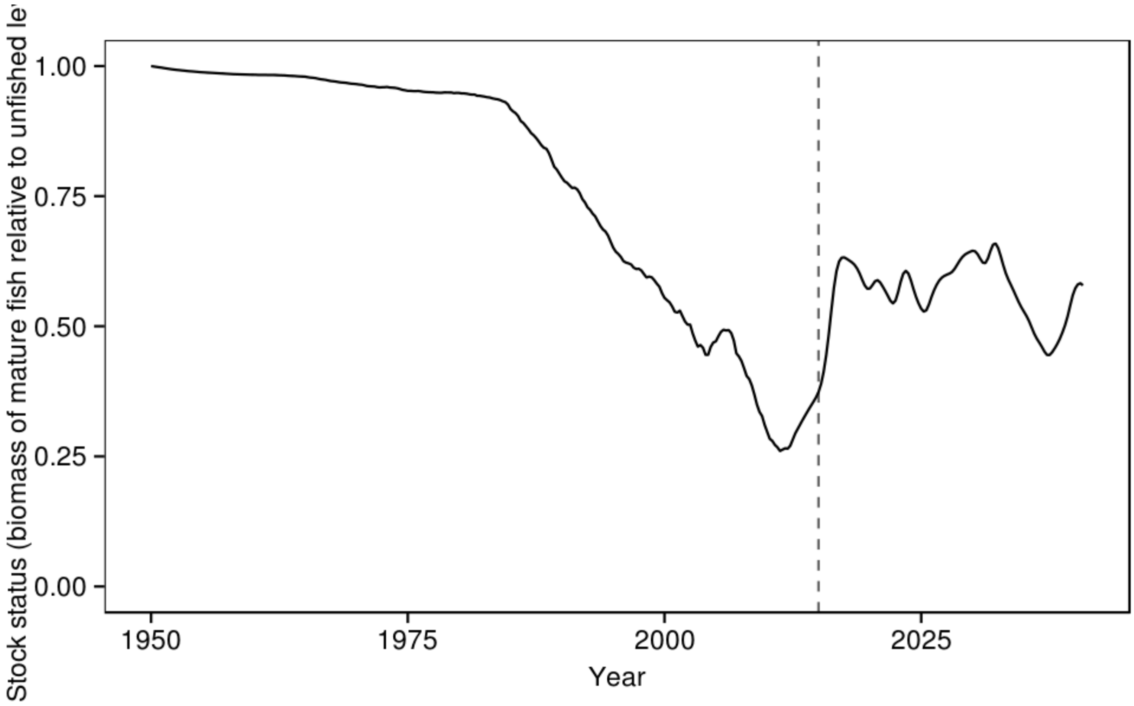
Deterministic recruitment (mil.)
0
300
600
900
1950
1975
2000
2025
Year



Recruitment deviation
0
1
2
3
1950
1975
2000
2025
Year



Biomass of mature fish



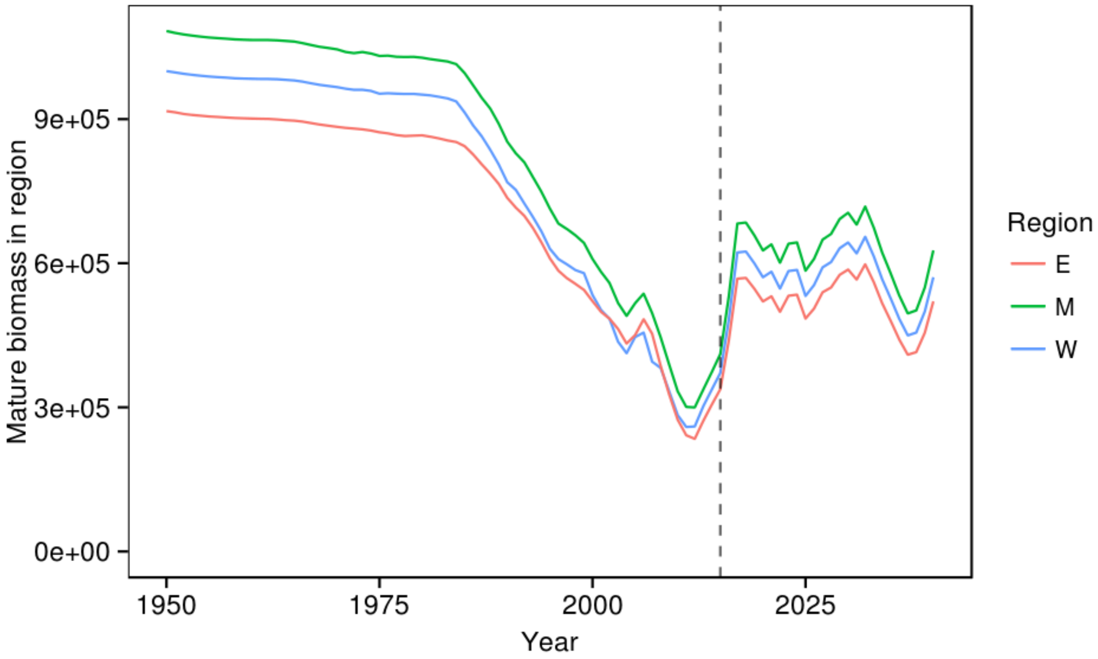
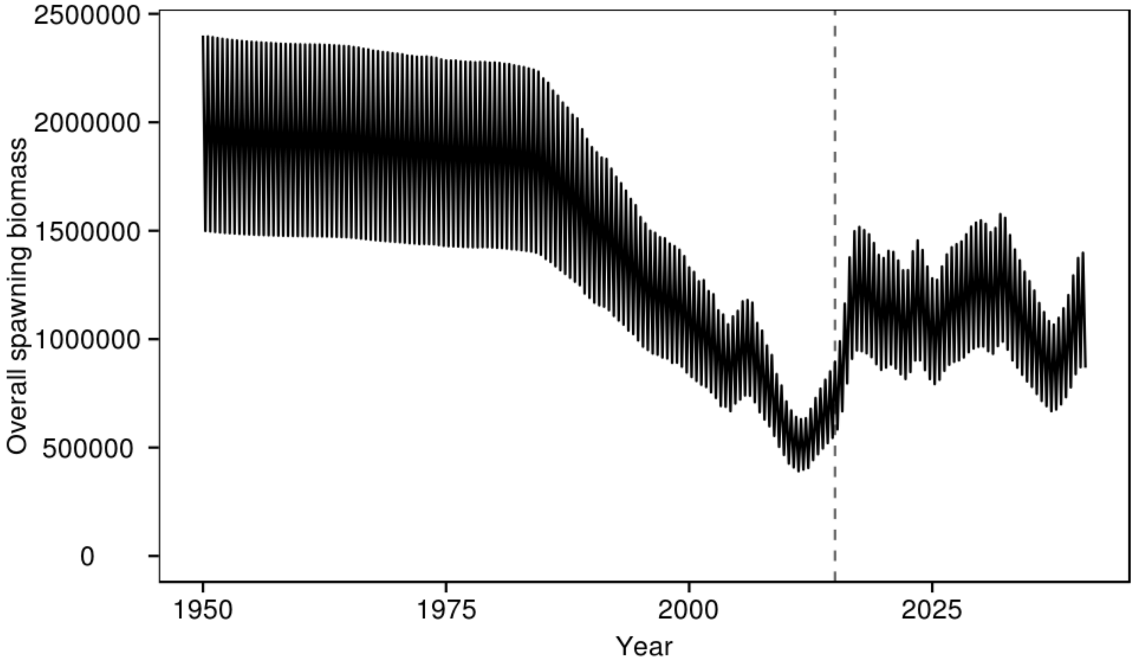


Figure 11 : Biomass of mature fish by region for the first quarter

Spawning biomass



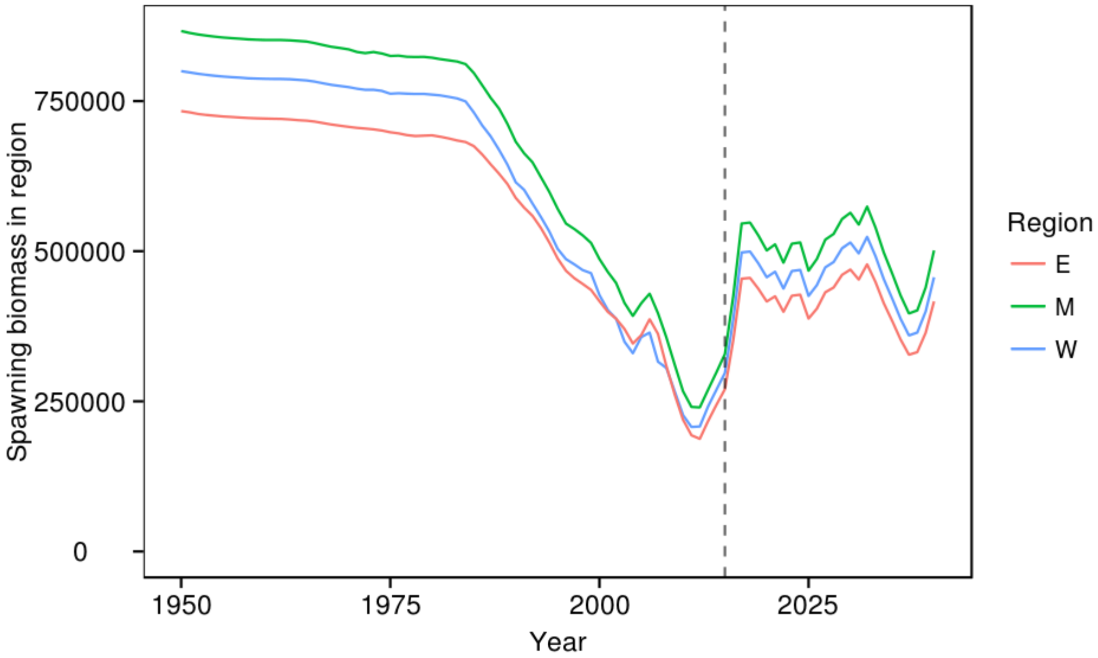
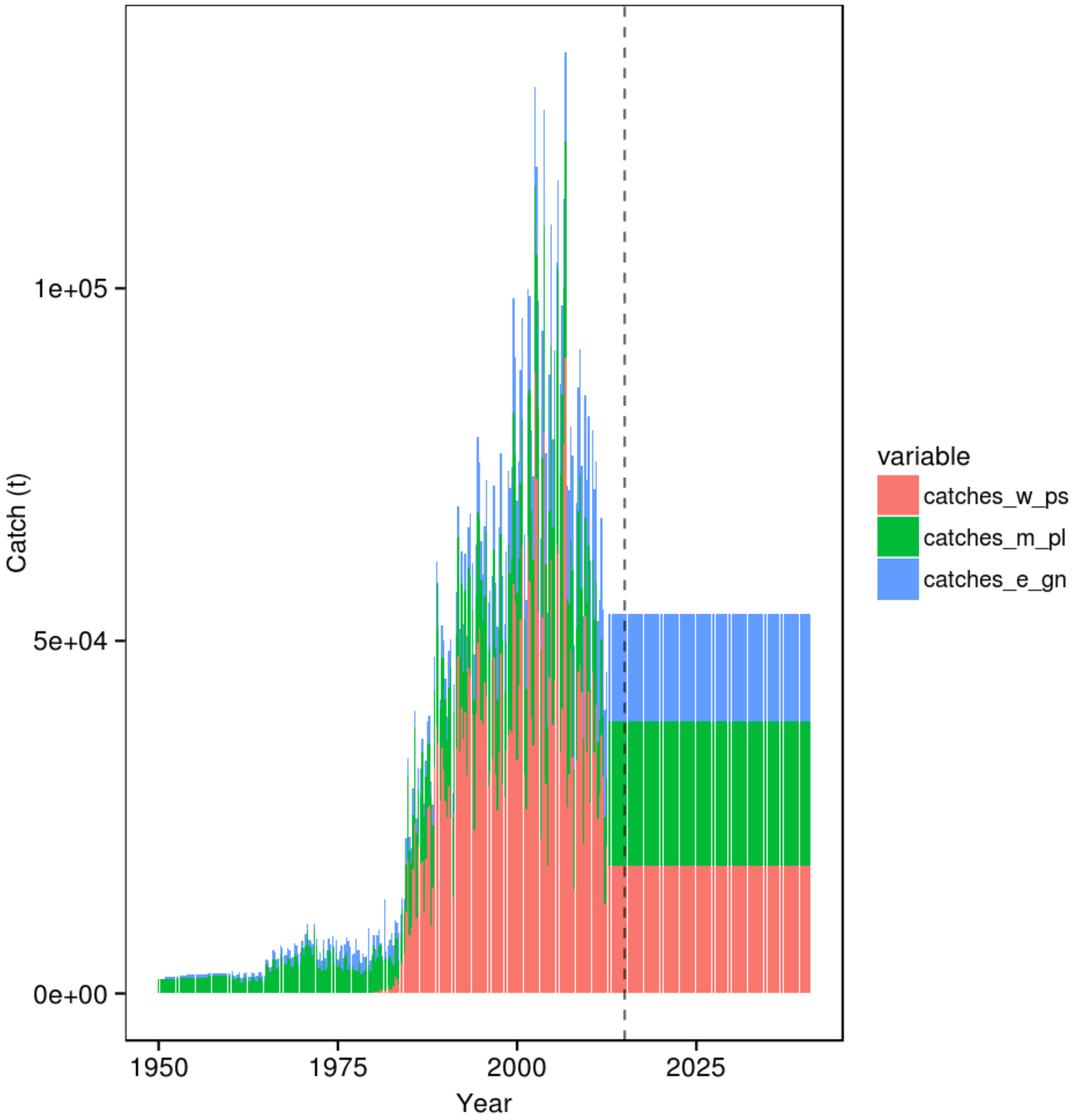


Figure 12 : Spawning biomass by region for the first quarter

Fishery



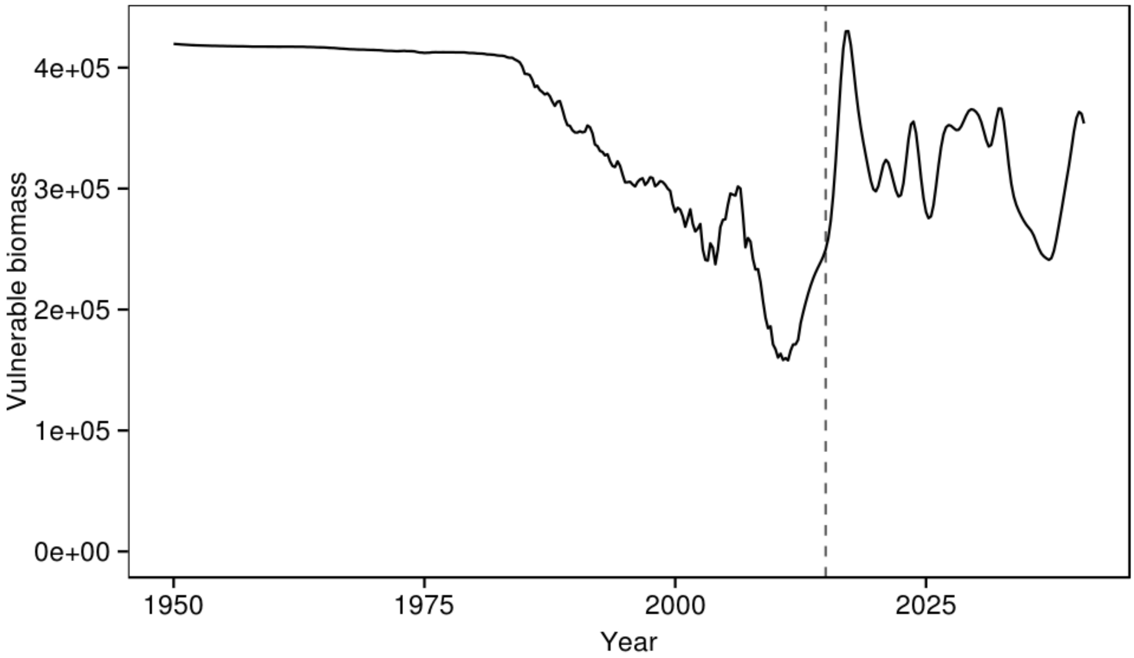


Figure 13 : Vulnerable biomass trajectory for West (W) pusrse siene (PS)

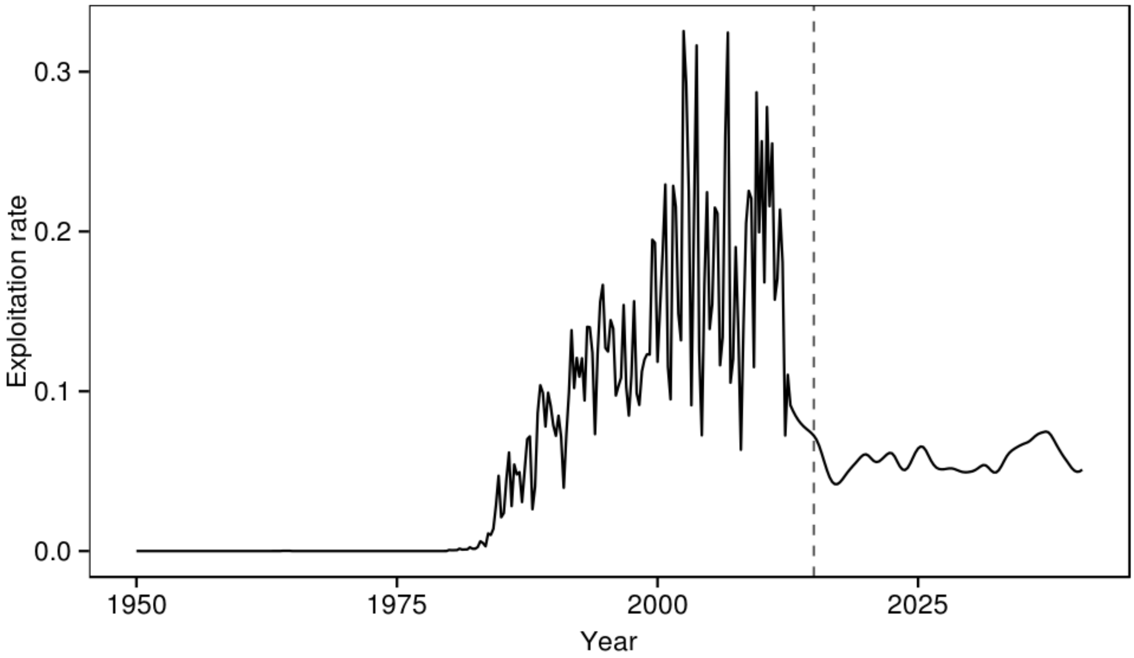


Figure 14 : Exploitation rate trajectory for West (W) pusrse siene (PS)

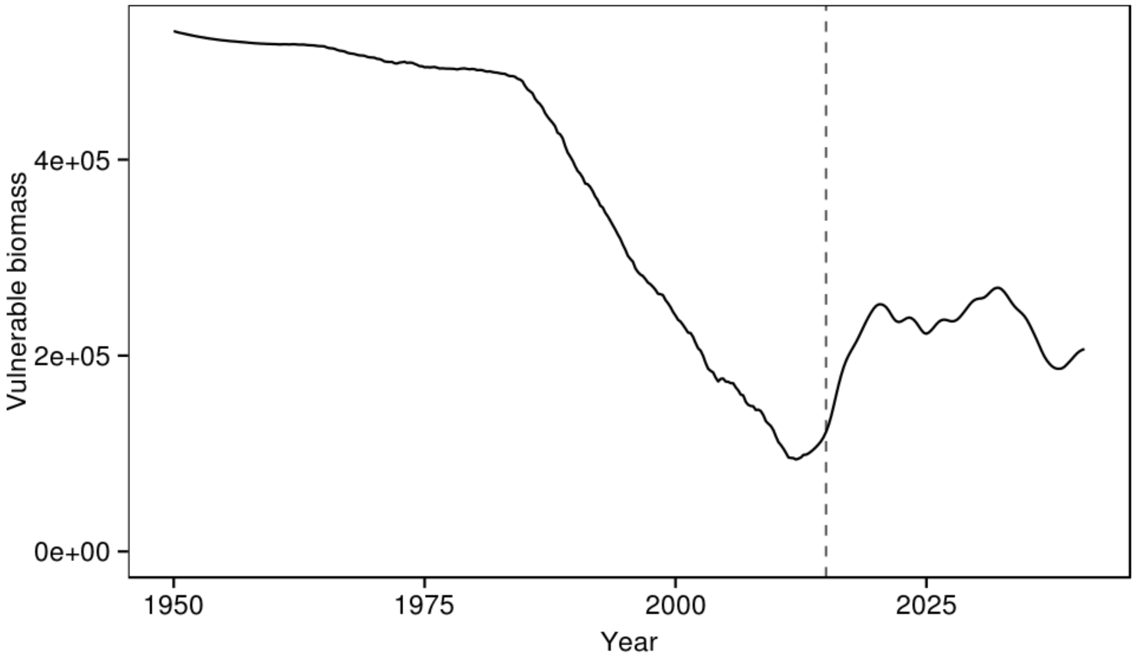


Figure 15 : Vulnerable biomass trajectory for Maldive (M) pole and line (PL)

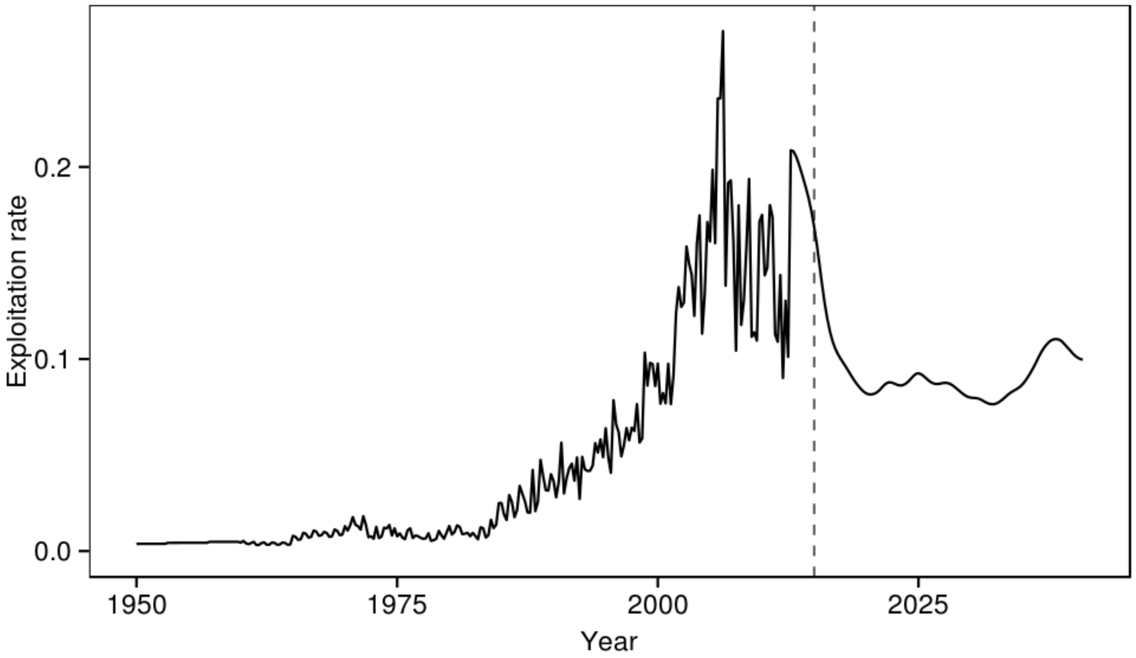


Figure 16 : Exploitation rate trajectory for Maldive (M) pole and line (PL)

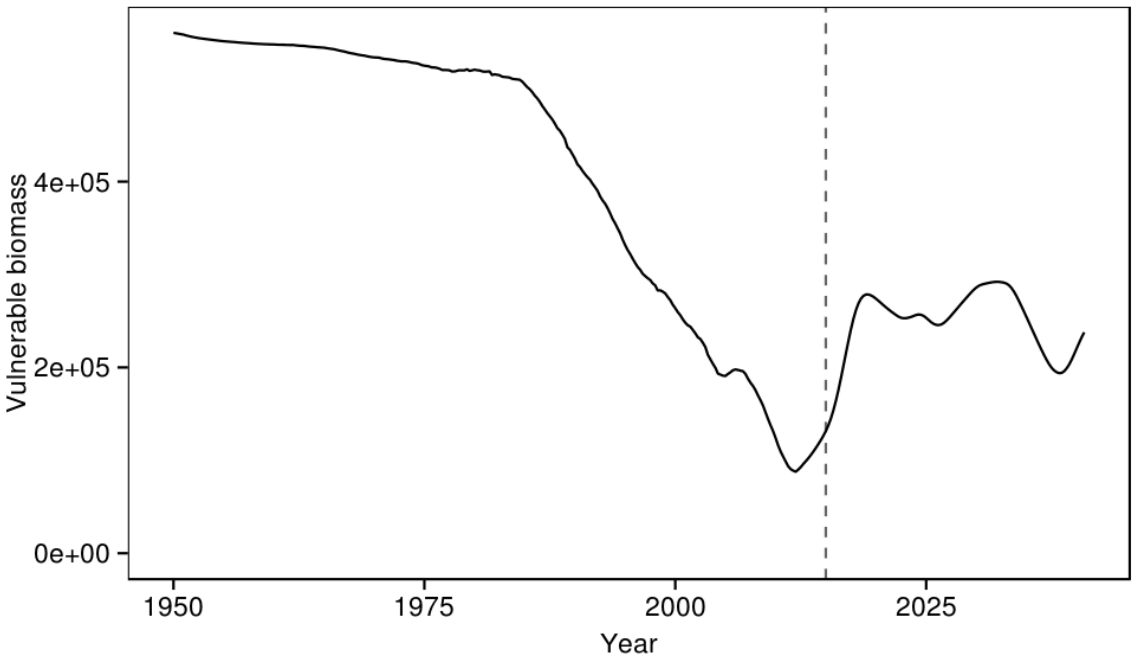


Figure 17 : Vulnerable biomass trajectory for East (E) gill net (GN)

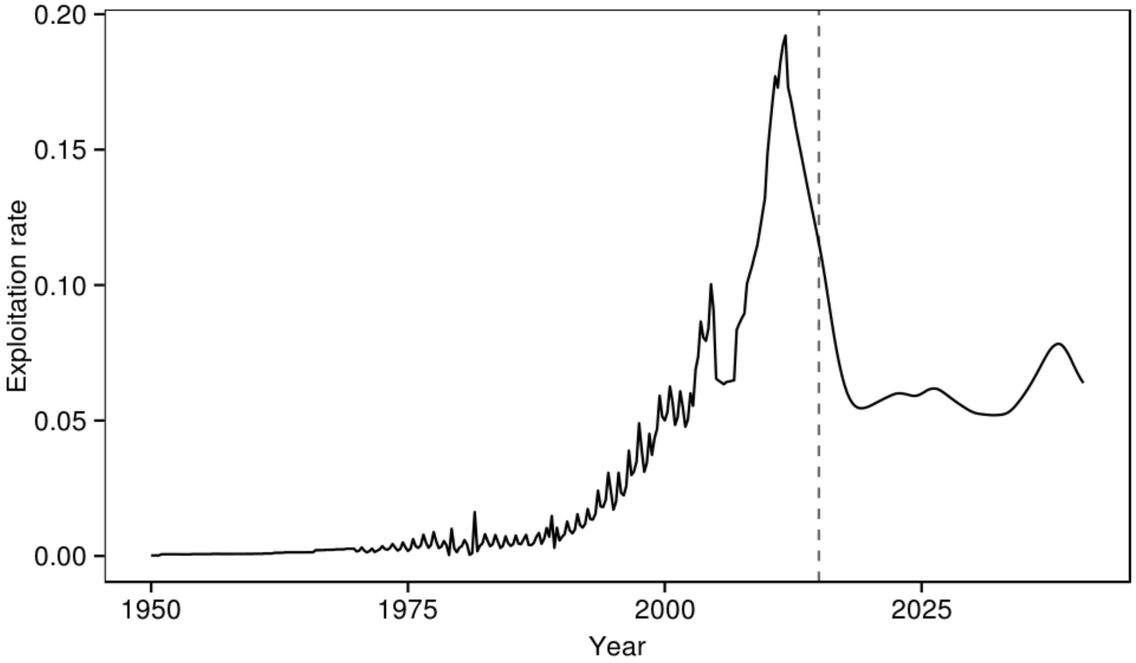


Figure 18 : Exploitation rate trajectory for East (E) gill net (GN)

Indian Ocean skipjack model : data fits

This document displays fits to the data generated from the `run` task (i.e. `./ioskj.exe run`) which uses the default parameter values (those marked `#value`) defined in `parameters/input/parameters.cila` . 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.

Maldive (M) pole and line (PL) CPUE

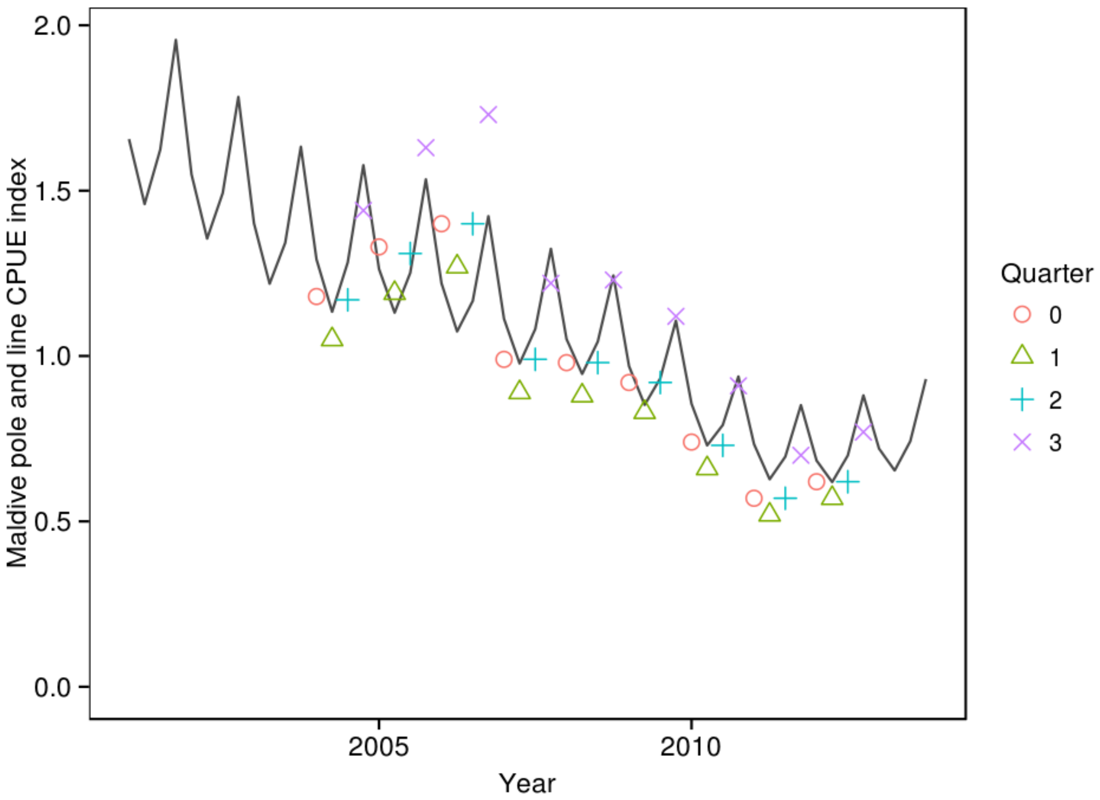


Figure 1 : Observed (points) and expected (lines) Maldive (M) pole and line (PL) CPUE.

Western (W) purse seine (PS) CPUE

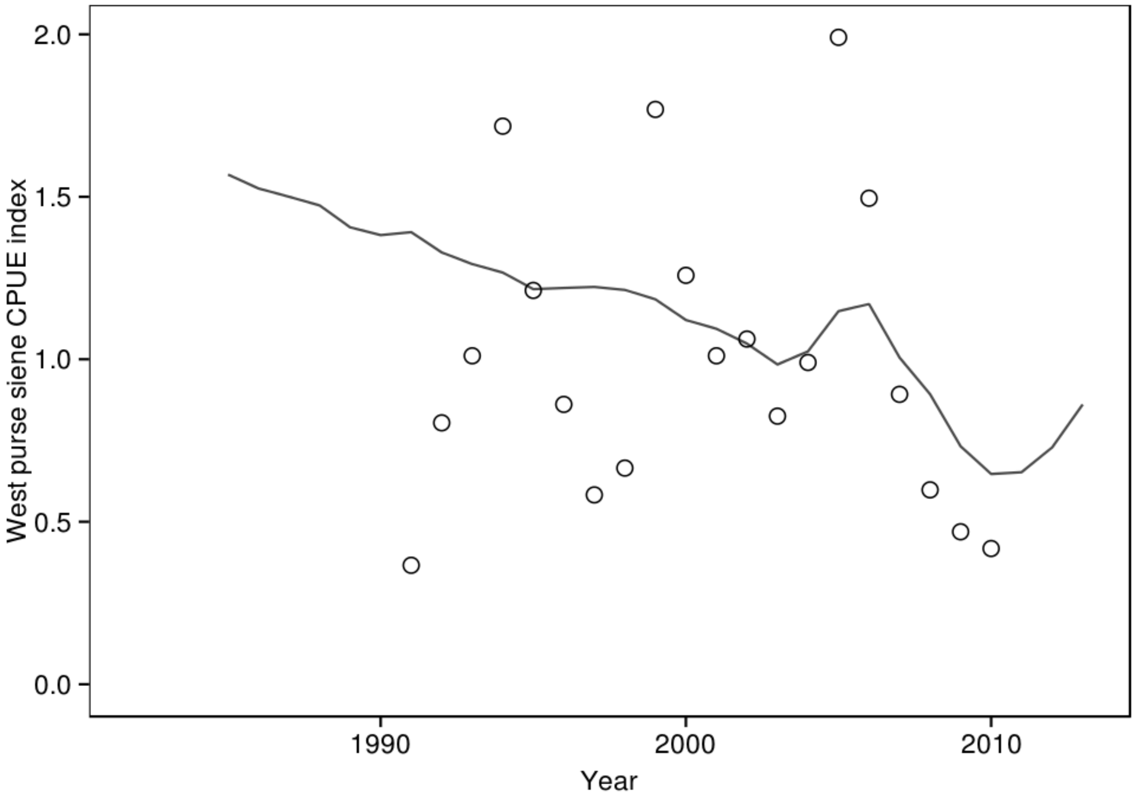


Figure 2 : Observed (points) and expected (lines) western (W) purse seine (PS) CPUE.

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

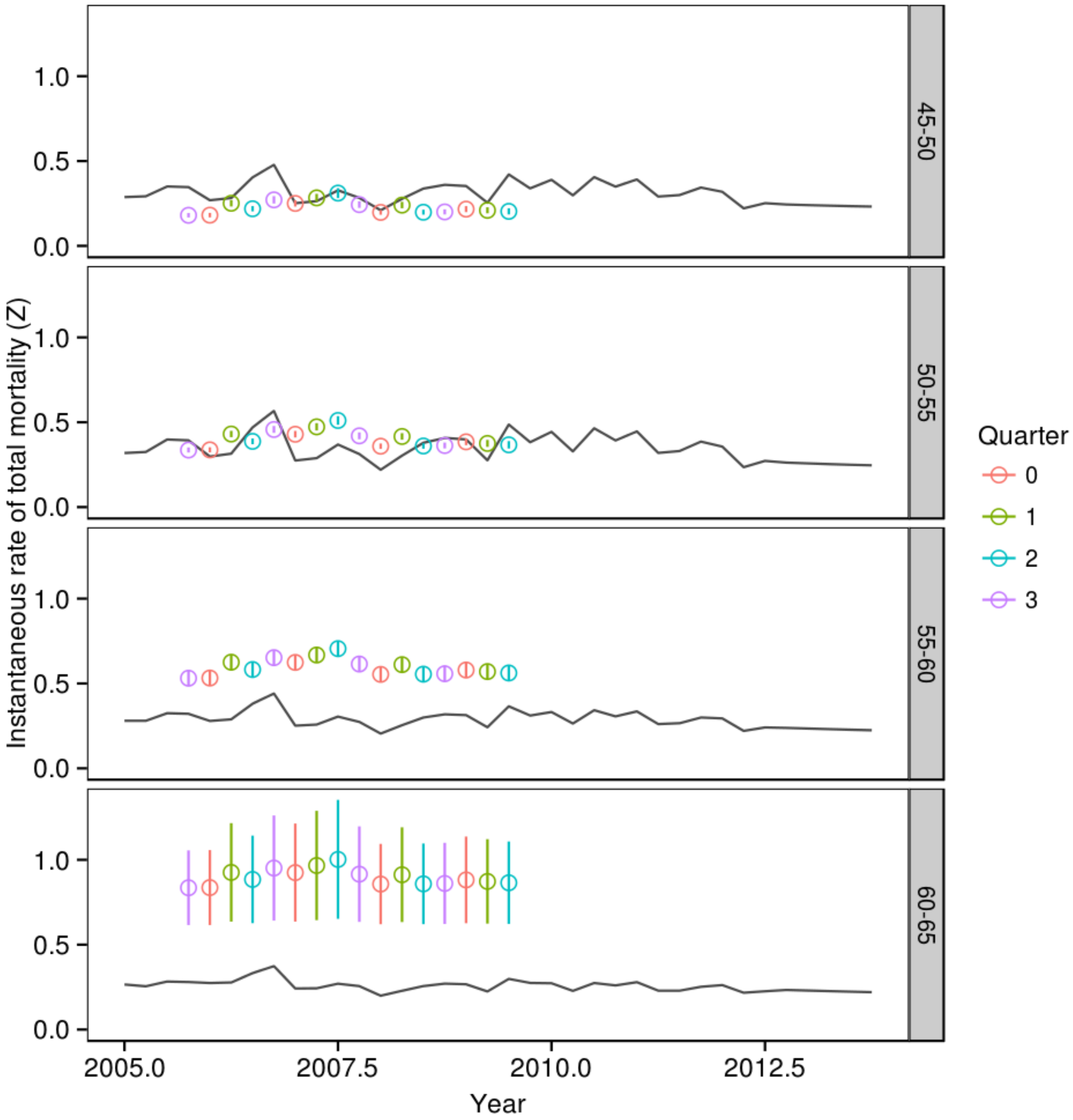


Figure 3 : Observed (points) and expected (lines) western (W) purse seine (PS) tagging Z estimates. Error bars indicate +/- one standard error in estimates.

Size frequencies

Mean length by region, method, year and quarter

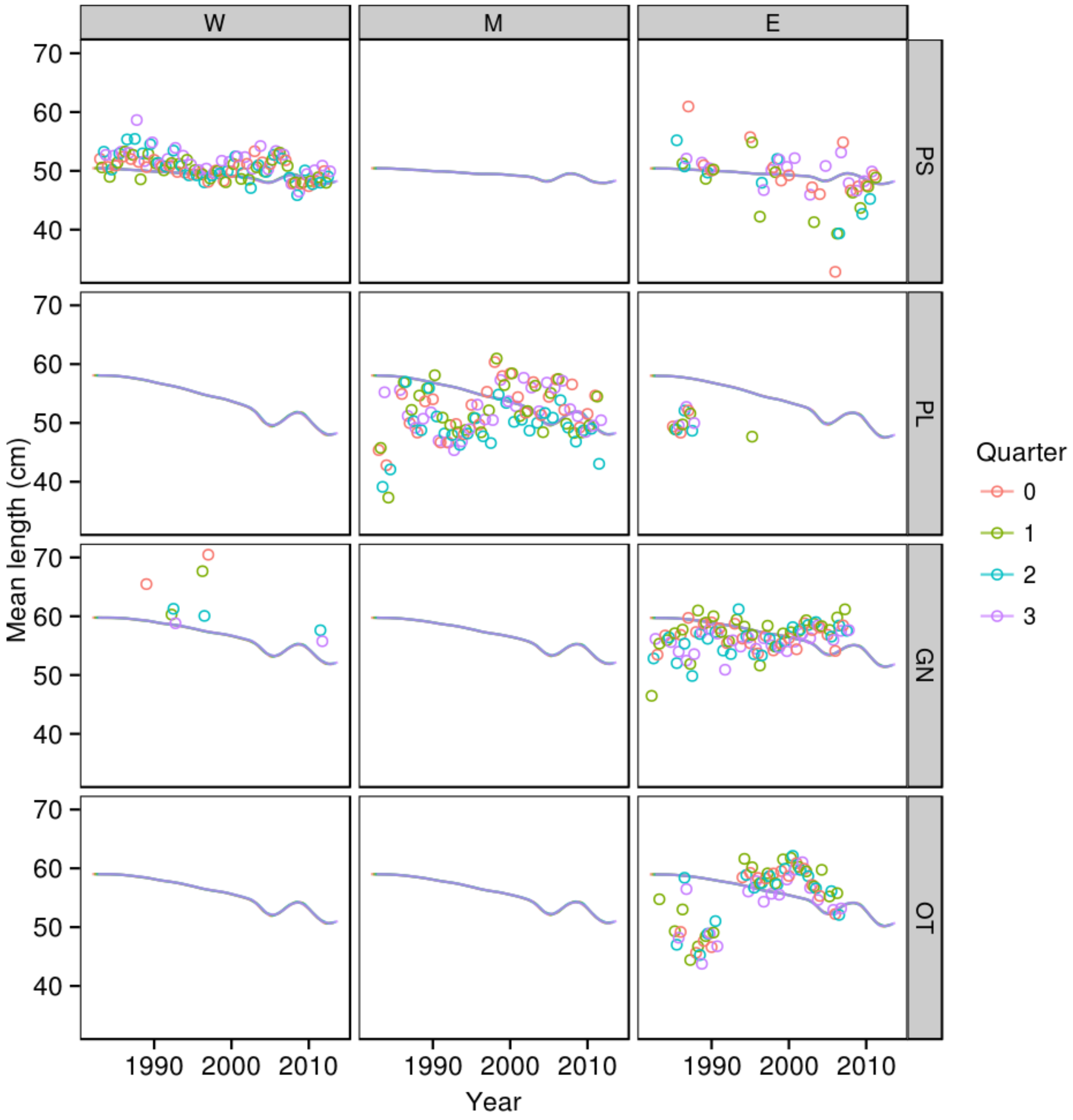


Figure 4 : Observed (points) and expected (lines) mean length of catch by region, method, year and quarter.

By region, method & quarter (aggregated over years)

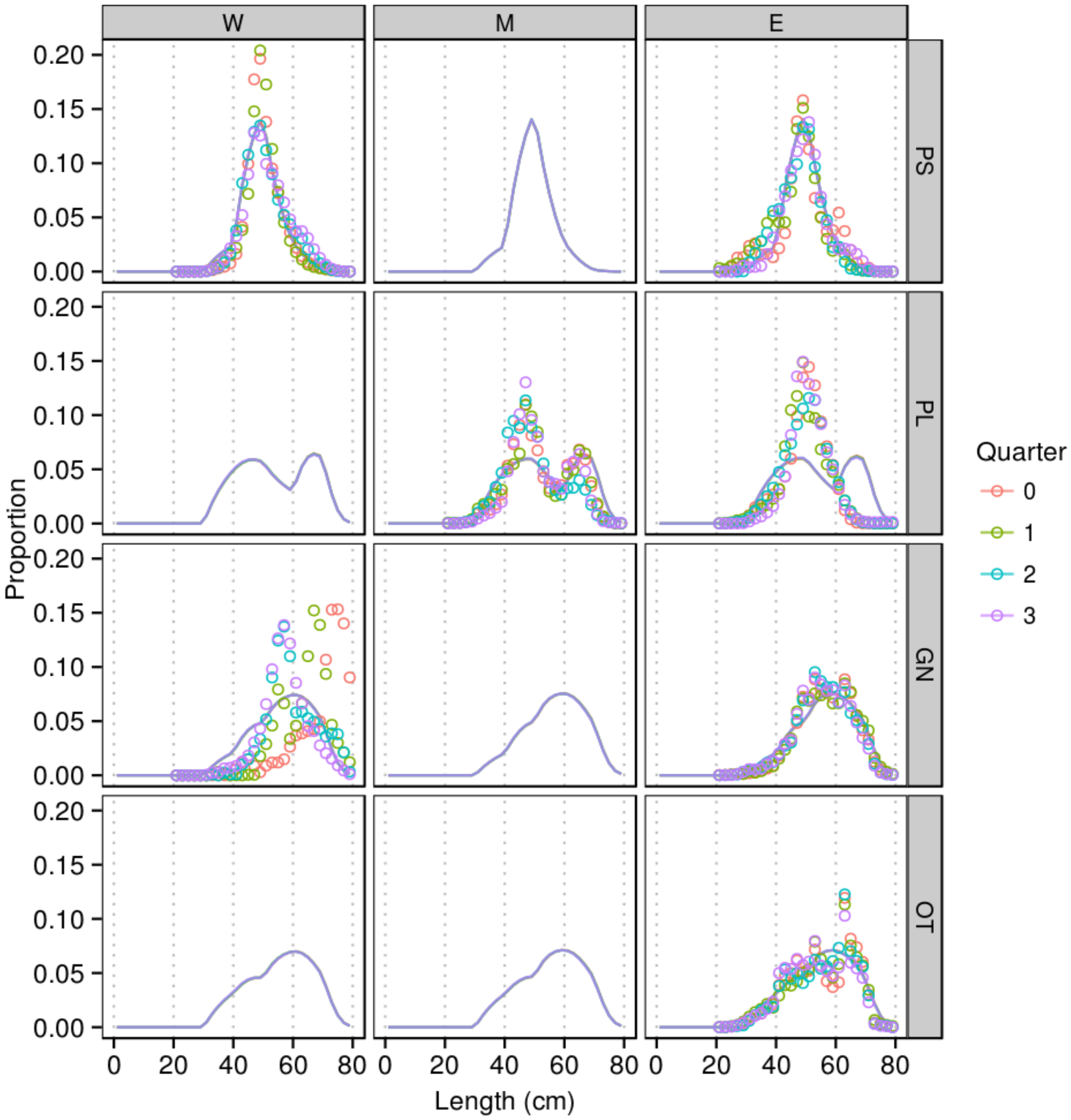


Figure 5 : Observed (points) and expected (lines) proportion of catch in each length class by region, method & quarter (aggregated over years).

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

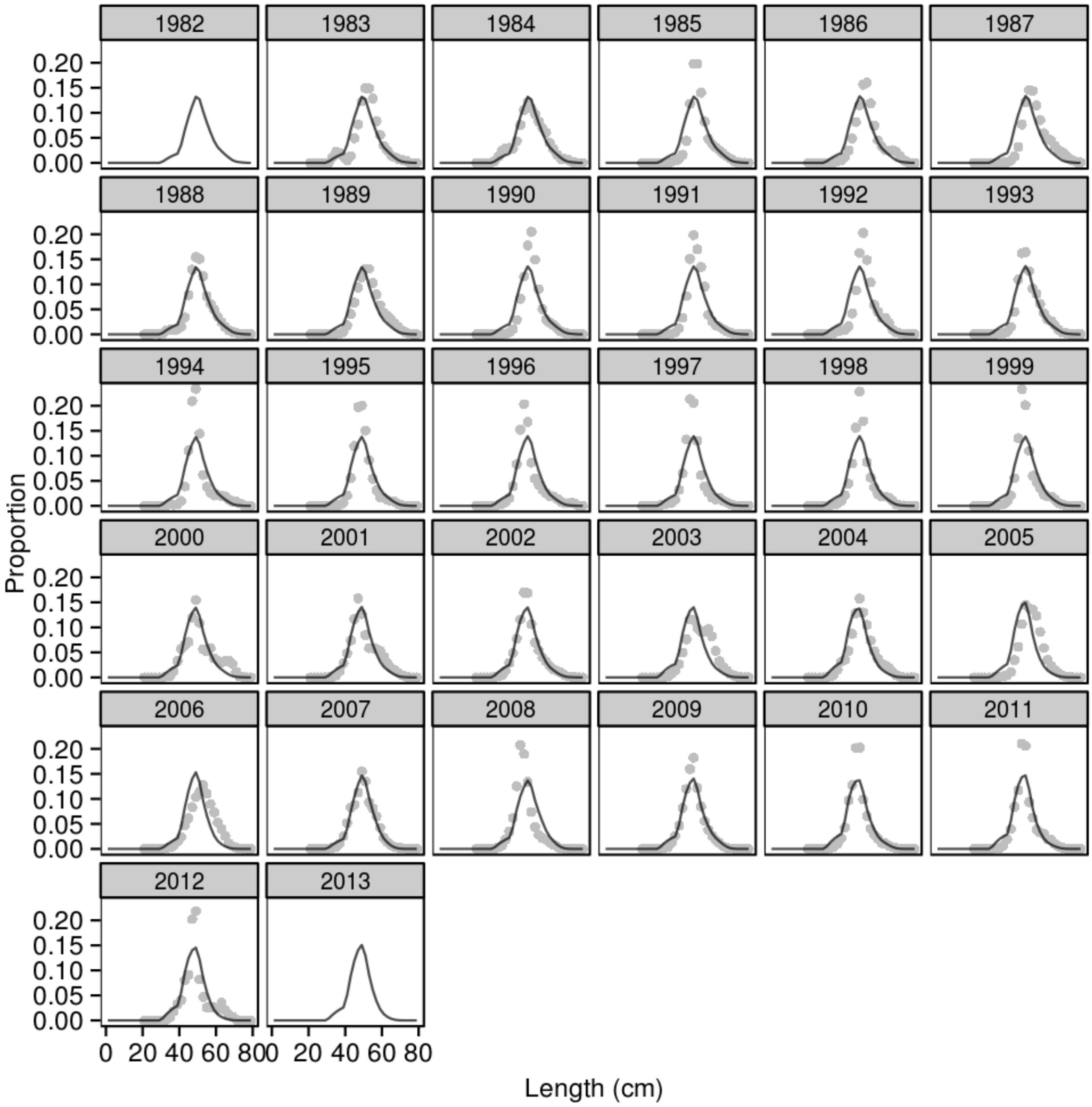


Figure 6 : Observed (points) and expected (lines) size frequency distributions for purse seine (PS) in the western region (W)

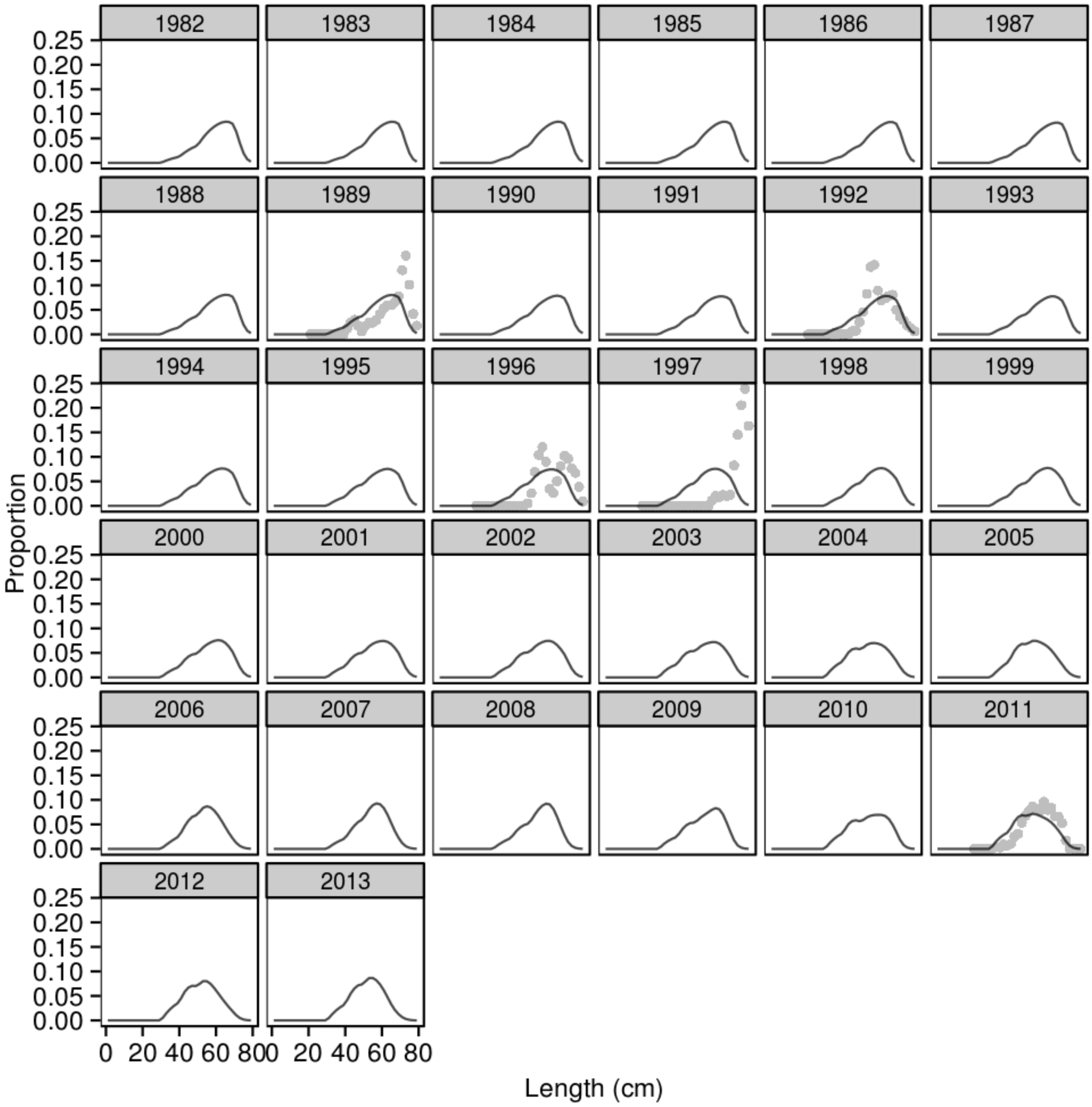


Figure 7 : Observed (points) and expected (lines) size frequency distributions for gillnet (GN) in the western region (W)

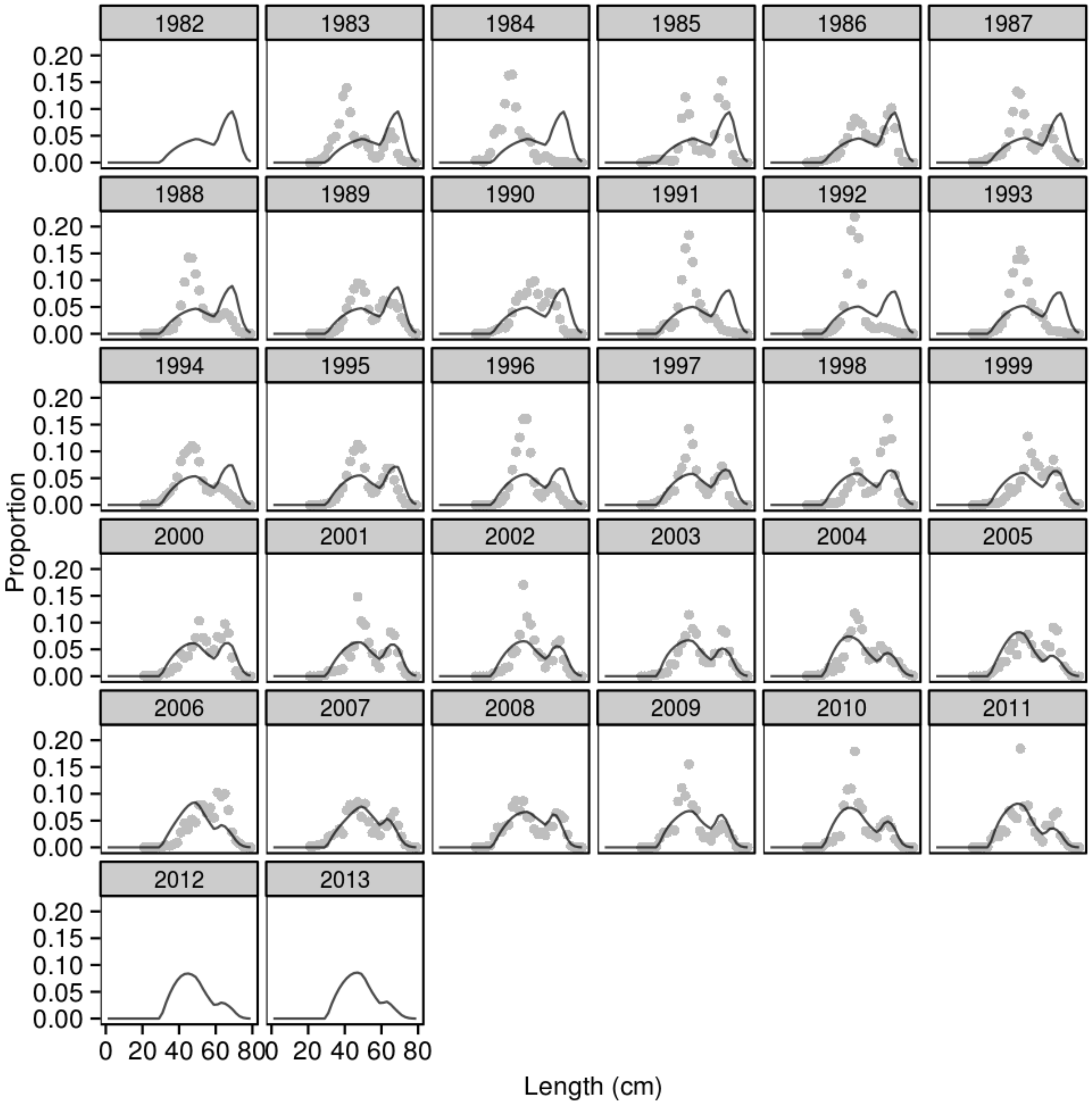


Figure 8 : Observed (points) and expected (lines) size frequency distributions for pole and line (PL) in the Maldive region (M)

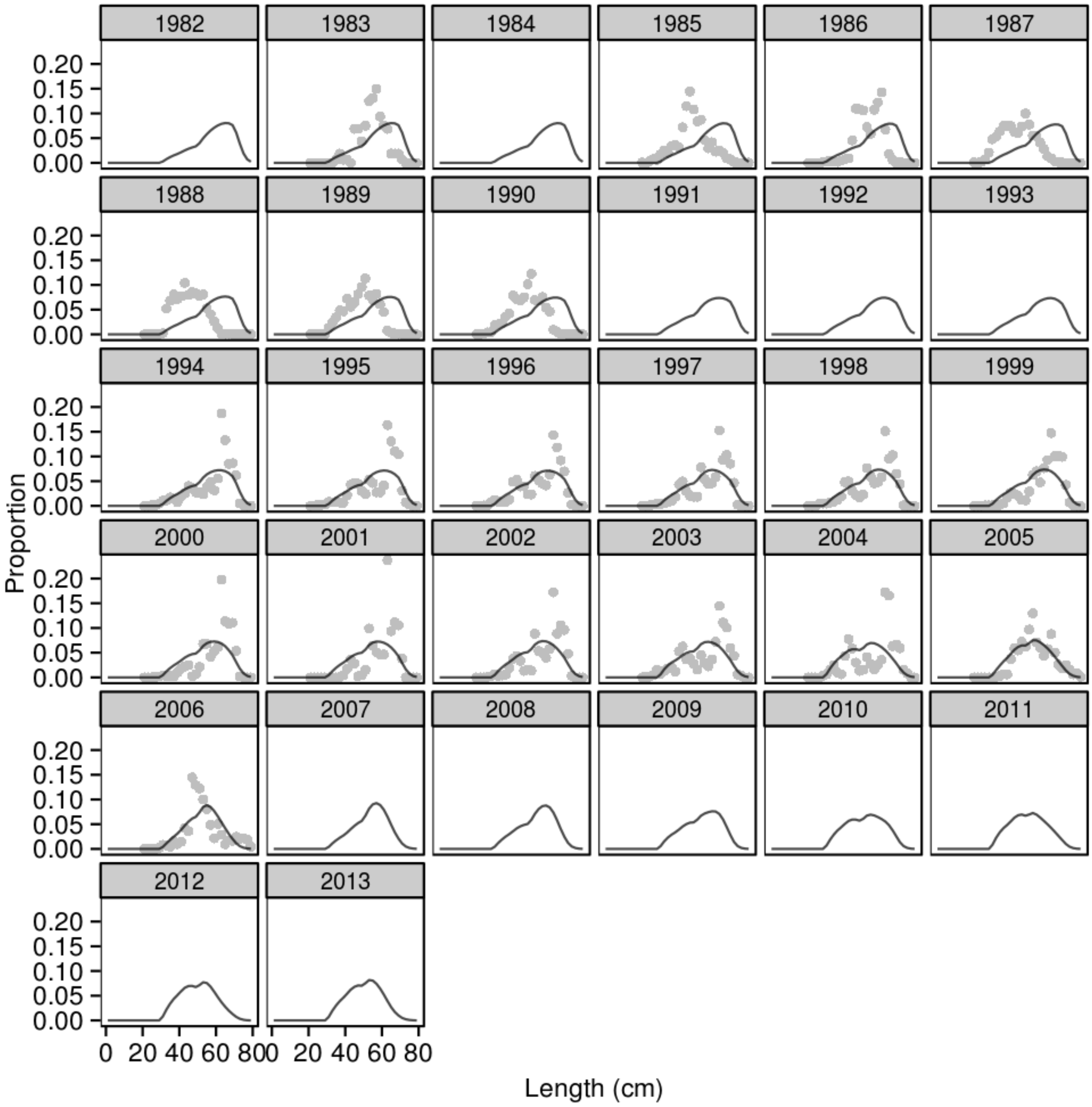


Figure 9 : Observed (points) and expected (lines) size frequency distributions for other methods (OT) in the eastern region (E)

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

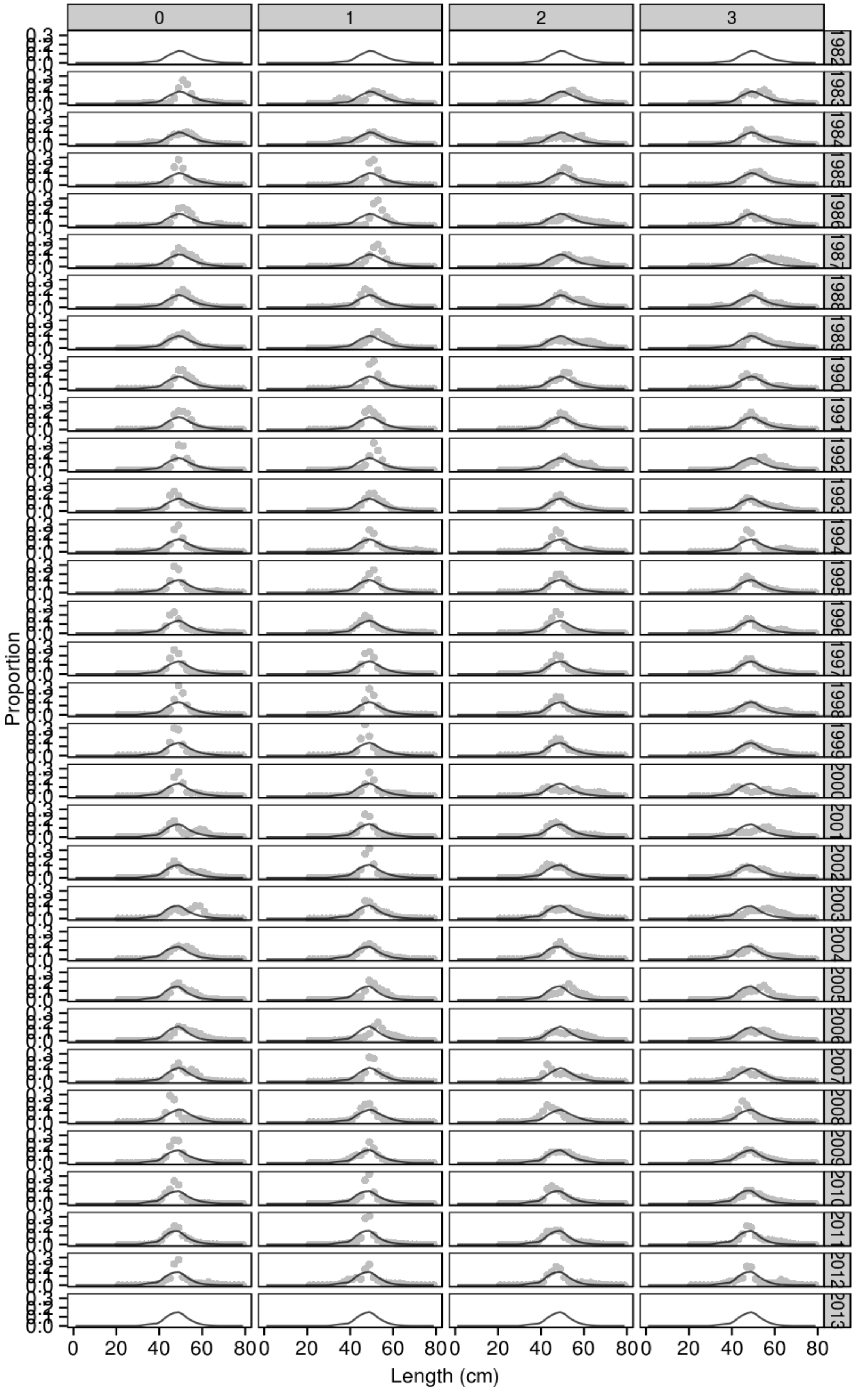


Figure 10 : Observed (points) and expected (lines) size frequency distributions for purse seine (PS) in the western region (W)

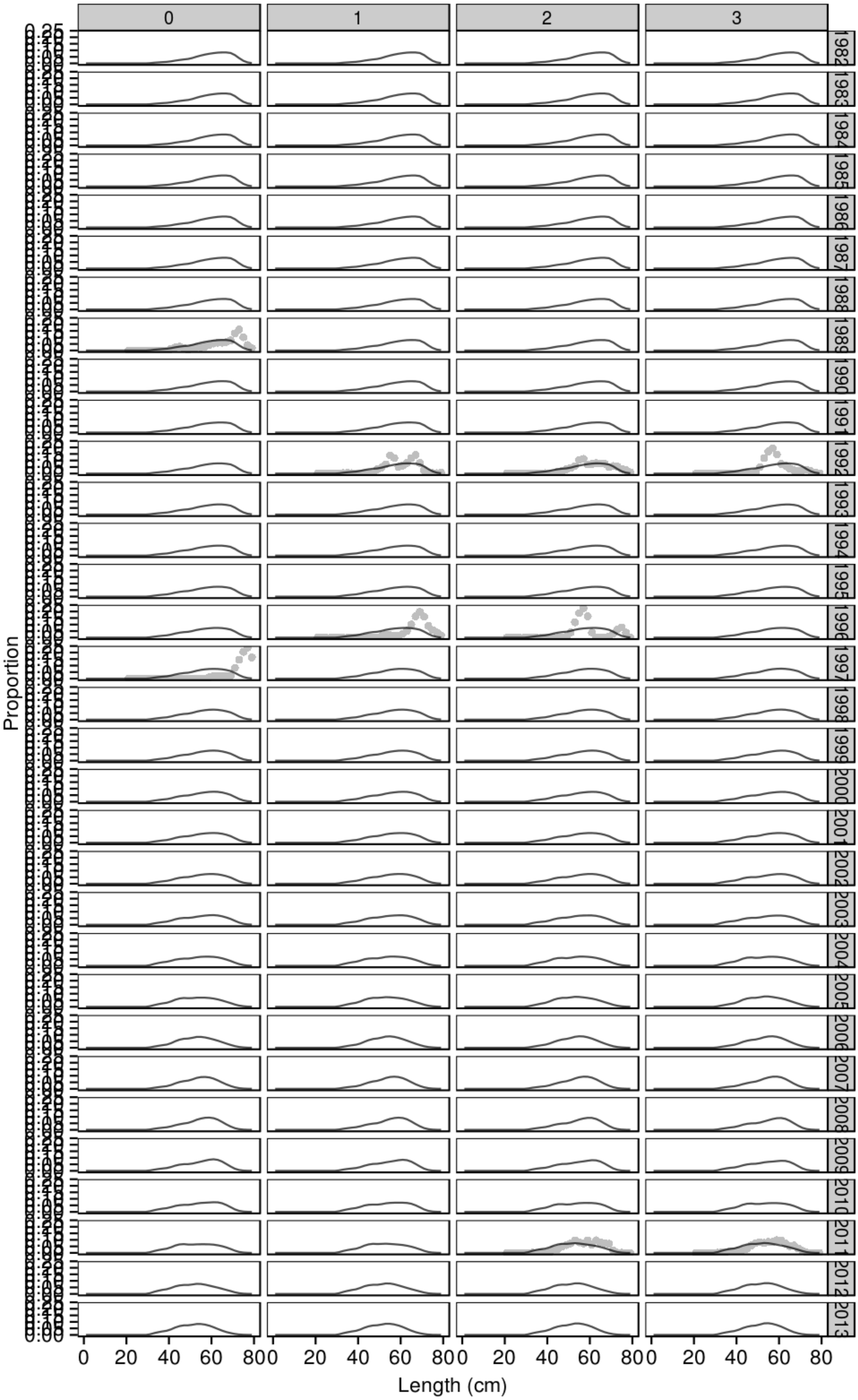


Figure 11 : Observed (points) and expected (lines) size frequency distributions for gillnet (GN) in the western region (W)

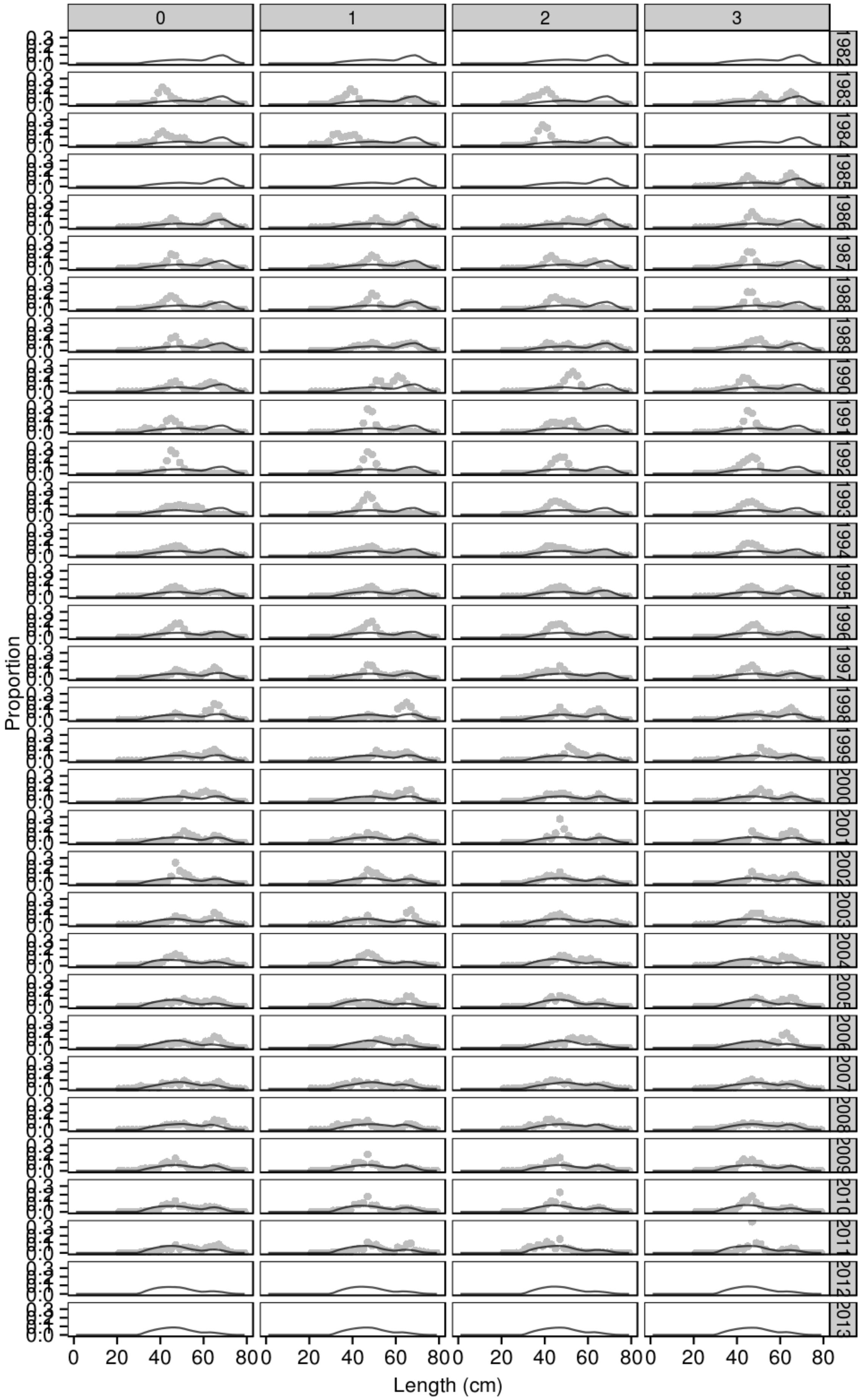


Figure 12 : Observed (points) and expected (lines) size frequency distributions for pole and line (PL) in the Maldive region (M)

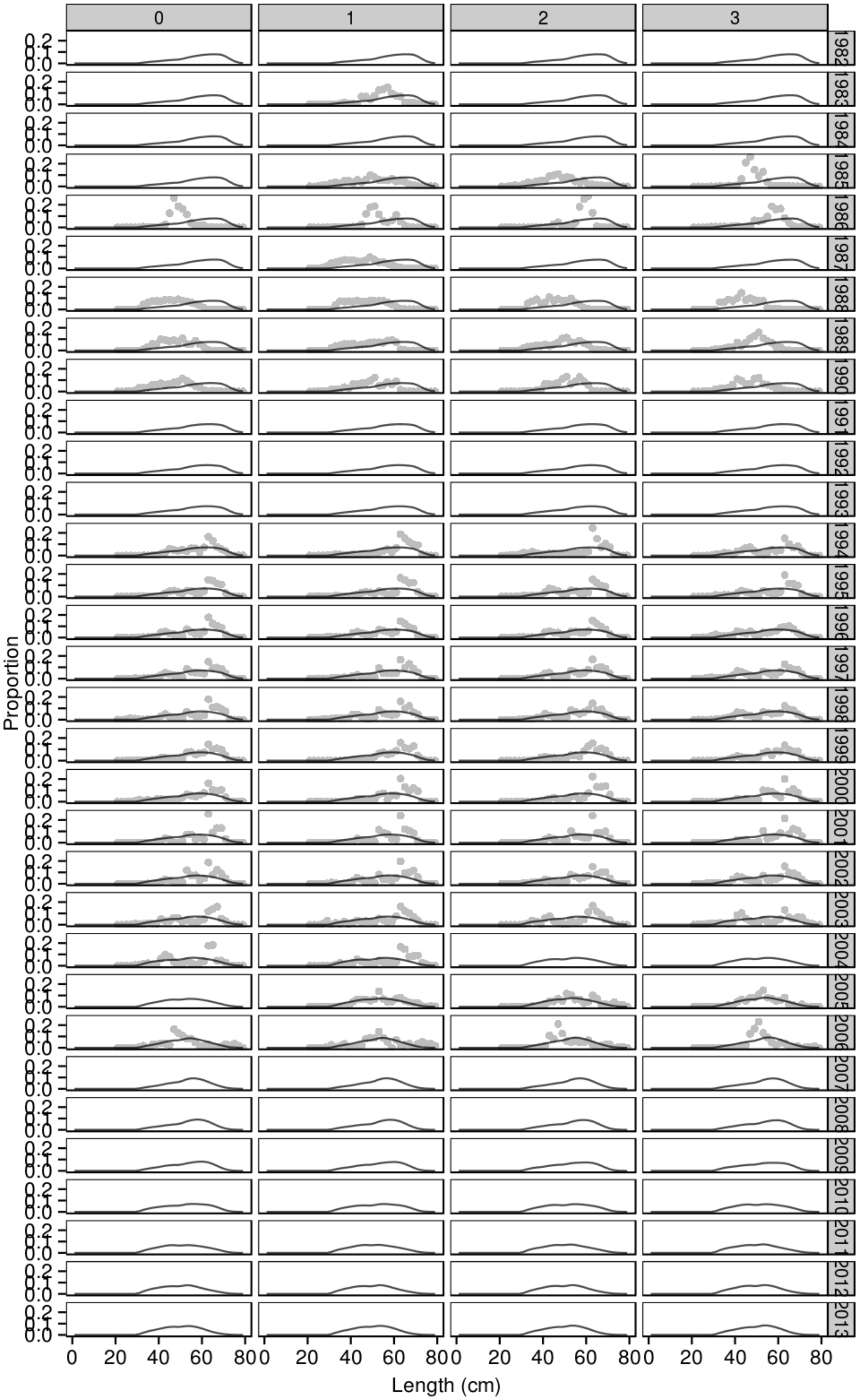


Figure 13 : Observed (points) and expected (lines) size frequency distributions for other methods (OT) in the eastern region (E)

Indian Ocean skipjack model : description of management procedures

DRAFT

This documentation is a draft under active development. As such, it may not exactly mirror what is in the current version of the code. Separate documentation, generated from the model's C++ source code, is also available .

Introduction

This document describes the management procedures (MPs) evaluated in this study. Several classes of MP are considered with each *class* having several *control parameters* which can be varied to alter it's behaviour. We refer to a particular combination of control parameters for a class of MP as an instance of that class.

The classes of management procedure used here are mainly intended to illutrate the wide variety of possible MPs : the data inputs they use, their algorithmic form and the magagement controls which they alter (e.g. effort versus catch). The

BRule class

The `BRule` class of MP is similar to generic harvest control rules that have been suggested in other tuna fisheries (e.g. SCRS 2011, Scott et al 2013). It assumes that an estimate of stock status is available each year (although the same MP could be altered to have less frequent updates) and uses a simple relation between stock status and fishing intensity. Here we define relative stock status as ratio of current spawning biomass over the spawning biomass associated with maximum sustainable yield, $\frac{B_t}{B_{msy}}$, and relative fishing intensity as the ratio of the current instantaneous rate of fishing mortality and the rate associated with MSY, $\frac{F_t}{F_{msy}}$. For this study we have investigated the impact of alternative levels of stock assessment precision and implementation error on performance statistics.

In each year the relative biomass is estimated through a stock assessment,

$$\hat{S} = \frac{B_t}{B_{msy}} \varepsilon$$

where ε is a lognormally distributed multiplicative error with mean of 1 and standard deviation of p ,

$$\varepsilon \sim LN\left(1, p\right)$$

Using $\hat{S}$ the recommended fishing intensity ($\overline{F}$) is calculated. If $\hat{S} \& <; s_l$ then,

$$\overline{F} = 0$$

If $\hat{S} \& >; s_t$ then,

$$\overline{F} = f$$

Otherwise,

$$\overline{F} = \frac{f}{s_t - s_l} \left(\hat{S} - s_l\right)$$

The recommended fishing intensity is applied to the fishery in the following year,

$$F_{t+1} = \overline{F}\varphi$$

where φ is a lognormally distributed multiplicative error with mean of 1 and standard deviation of e ,

$$\varphi \sim LN(1, e)$$

Table 1 provides a summary of each of the control parameters of `BRule` and their respective values evaluated in this study. Note that IOTC Resolution 13/10 set an interim limit target biomass of B_{msy} (i.e. $b_t = 1$) and an interim limit biomass of $0.4B_{msy}$ (i.e. b_l = 0.4). Analogous values have been tested. IOTC Resolution 13/10 also includes a limit reference point of $1.5F_{msy}$. Such a limit reference point on F is not a feature of this MP which instead is based on relative biomass reference points.

Table 1 : Control parameters of the BRule management procedure : description an values evaluated.

Parameter	Symbol	Description	Values evaluated
Estimation precision	p	Precision with which relative stock status is estimated	0, 0.2, 0.4, 0.6
Threshold stock status	s_t	Relative stock status below which recommended fishing intensity is reduced	0.7, 0.8, 0.9, 1.0
Limit stock status	s_l	Relative stock status below which recommended fishing intensity is zero	0.2, 0.3, 0.4, 0.5
Target fishing intensity	f	Relative fishing intensity	0.8, 0.9, 1.0, 1.1
Implementation precision	e	Precision with which recommended fishing intensity is applied	0, 0.2, 0.4, 0.6

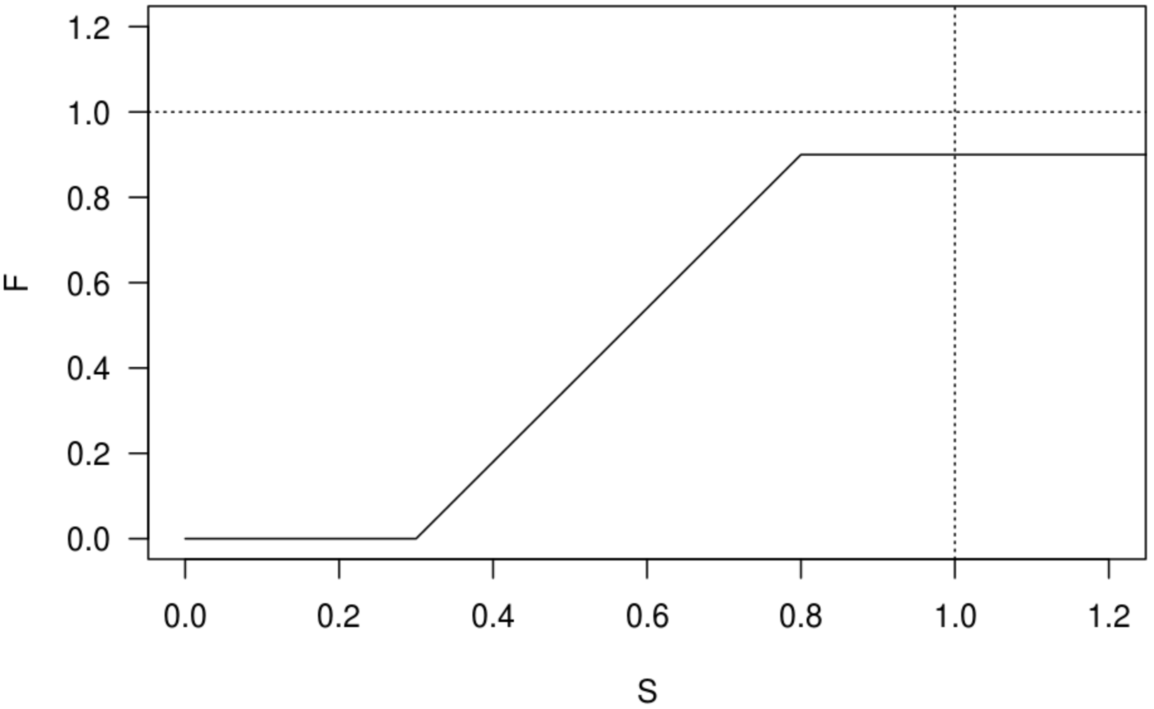


Figure 1 : An example instance of the BRule management prodedure with $s_l = 0.3$, $s_t = 0.9$, $f = 0.9$ showing the relation between $\widehat{S}$ and $\overline{F}$.

FRange class

`FRange` seeks to maintain the fishing mortality rate within a defined range. At periodic intervals, defined by the control parameter i , F is estimated (e.g. from a stock assessment or a tagging study) with a defined level of precision, p ,

$$\widehat{F} = F\varepsilon$$

where ε is a lognormally distributed multiplicative error with mean of 1 and standard deviation of p ,

$$\varepsilon \sim LN(1, p)$$

The estimated fishing mortality is compared to a range defined by two control parameters, f the centre of the range and b the buffer, or width, of the range.

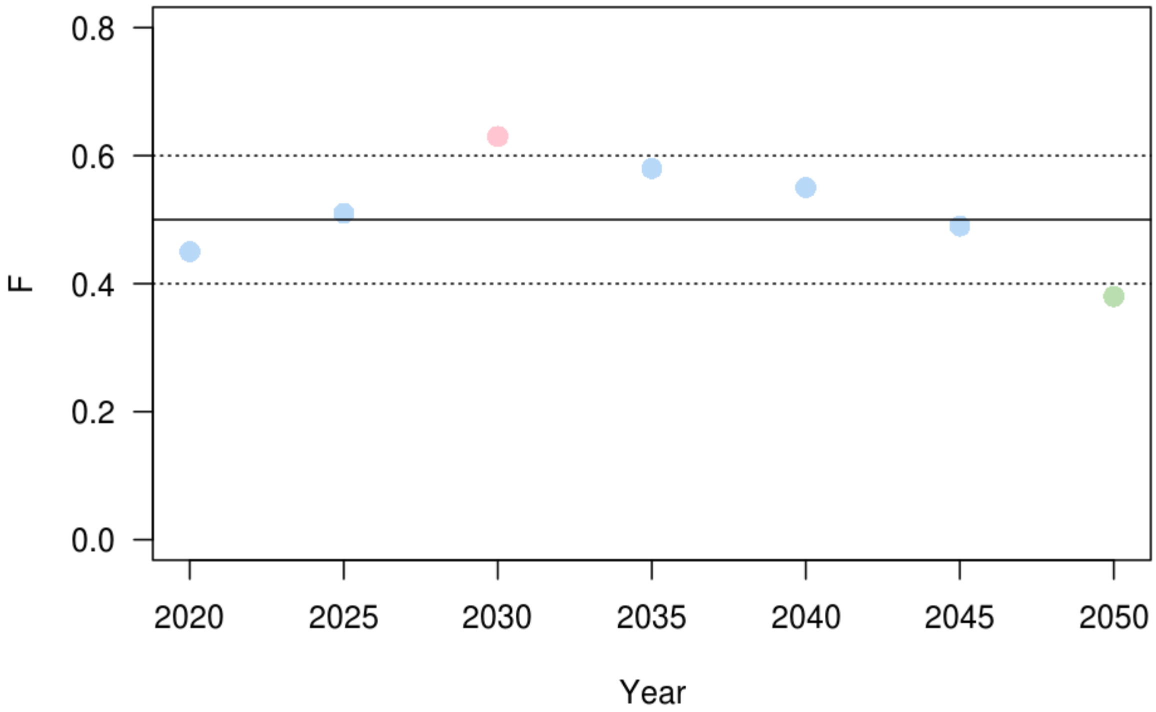


Figure 2 : An example instance of the BRule management prodedure with $i = 5$, $f = 0.5$, $b = 0.1$ illustrating how total allowable catches are increased (green circles) or decreased (red circles) when the estimated fishing mortality is below or above the target range.

References

Gerald P Scott, Gorka Merino, Haritz Arrizabalaga, Hilario Murua, Josu Santiago and Victor R. Restrepo, 2013. A Framework for Promoting Dialogue on Parameterizing a Harvest Control Rule with Limit and Target Reference Points for North Atlantic Albacore. SCRS/2013/120

SCRS, 2011. Report of the 2011 joint meeting of the ICCAT Working Group on Stock Assessment Methods and Bluefin tuna Species Group to analyze assessment methods developed under the GBYP and electronic tagging. http://www.iccat.int/Documents/Meetings/Docs/2011_WG%20METHODS-ENG.pdf