Department of Employment, Economic Development and Innovation
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Reference points for the Queensland scallop fishery

A. B. Campbell, M. F. O'Neill, G. M. Leigh, Y-G Wang and E. J. Jebreen

Project No. 2009/089

The University of Queensland Australia

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1 Non technical summary

2009/089	Reference points for the Queensland scallop fishery

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OBJECTIVES:

1. Propose and construct a set of reference points for the scallop fishery
2. Test the reference points in the FRDC 2006/024 MSE framework

NON TECHNICAL SUMMARY:

OUTCOMES ACHIEVED TO DATE

The project delivered biological reference points for management of the Queensland saucer scallop fishery. They will allow the fishery to be sustainably and profitably managed which will benefit all involved in the Queensland scallop fishery. Specifically, the project contributed to the following outcomes:

1. Updated estimation of stock status using improved methodology and integrated multiple previously unused data sources including Vessel Monitoring System data, fishery-independent survey data and historical catch and catch-rate data.
2. Constructed a framework for evaluating spatio-temporal and other management strategies in relation to equilibrium reference points MSY and Emsy, and an indicator of catch rate.
3. Ascertained that, irrespective of management strategy, and assumptions on historical data, MSY for the fishery is around 500 to 800 tonnes.
4. Provided evidence that a 95 mm minimum legal size during the winter months leads to a marginally higher MSY than the current 90 mm year round system.
5. Provided evidence that a three-year, pulse-fishery oriented closure schedule leads to modestly higher values of the catch rate indicator.
6. The project delivered a set of reference points to implement within the Fisheries Queensland plan review.
7. The project better informed stakeholders and managers about the important need to spatially monitor and manage saucer scallops

The primary aim of this research was to further develop a modelling framework originally constructed in FRDC Project 2006/024 to enable the estimation of stock status and reference points for the Queensland saucer scallop fishery. Three interrelated features of this fishery make the estimation of robust reference points challenging: 1) highly variable recruitment, both temporally and spatially, 2) a fishing fleet that is able to target the high density areas, in space and time, with great accuracy, and 3) a history of management through spatio-temporal closures. These challenges were met by: a) spatially stratifying the framework at a relatively fine scale (many of the strata are 5 nautical miles squared), b) capturing spatio-temporal variability using a Bayesian state space approach for parameter estimation and linking this with spatially explicit equilibrium simulations, c) developing a novel effort allocation mechanism based on a ‘knowledge parameter’ which quantifies the effect of fisher targeting, and d) tuning the framework with fine-scale Vessel Monitoring System (VMS) data and fishery-independent survey data.

The framework consists of an estimation component, in which posterior distributions for parameters are estimated from data, and a simulation component, in which these distributions are used to project forward under different management regimes. Both were designed in a spatially explicit fashion so that the impact of various spatio-temporal closure management strategies could be quantified in terms of their impact on reference points. Maximum sustainable yield (MSY) and the corresponding effort (Emsy) were considered, along with an indicator of the potential for taking a given amount of yield with less effort. More elaborate reference points such as maximum economic yield (MEY) can be considered modularly in future work, now that the spatially explicit equilibrium simulation framework has been developed.

Reference points for four model variants and three management scenarios were considered. The results corresponded to two hypotheses on the stock-recruitment function: a very large stock with limited productivity (model one), or a smaller stock with increasingly greater productivity (models two through four). Median results from models one and two indicated that MSY was in the range of 500 to 600 tonnes. Median MSY from models three and four ranged from 700 to 800 tonnes. E_{MSY} was highly variable due to the possibility of two distinct hypotheses with similar fit to the data: a large, relatively unproductive stock, or a smaller, highly productive stock. For this reason we recommend working back from MSY, via target average catch rates, to arrive at sustainable effort levels.

Results relating to the management scenarios indicated that a minimum legal size (MLS) of 95mm through the winter months performed better, but only marginally, than the current 90mm year round limit in terms of MSY. A combination of the 95mm winter MLS and a modification of the current closure system from two years to three years, with closure cells closed for 33 months and open for 3, showed a 21% increase in the catch rate indicator over the current management settings for these factors.

KEYWORDS: saucer scallop, *Amusium balloti*, Bayesian state space, reference points, spatio-temporal closures

2 Acknowledgments

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3 Background

The spatially complex nature of scallop fisheries makes the construction of robust reference points difficult. FRDC project 1999/120, *Reference point management and the role of catch-per-unit-effort in prawn and scallop fisheries* (O'Neill *et al.* 2005), concluded, ‘new types of data are essential to improve the accuracy of stock assessments, such as spatial indices of abundance collected through fishery independent sampling and VMS’, and ‘more accurate and robust reference points may exist using these data’. FRDC project 2006/024, *Harvest strategy evaluation to optimise the sustainability and value of the Queensland scallop fishery* (Campbell *et al.* 2010), made effective use of both these data types to answer questions about the optimal timing of spatial closures and other management strategies. This work builds on these previous projects to derive reference points that incorporate spatial management.

The long-term annual reported catch from the Queensland scallop fishery from 1988-2000 was about 1,100 tonnes (meat weight) valued at $20-30 million. Landings varied between about 600 and 2,200 tonnes and annual fishing effort has also varied between about 9,000-22,000 boat-days over the same period, with a mean of about 15,500 boat-days. The majority of the catch is exported, mainly to niche markets in south east Asia where it commands premium prices. In the last three years catch and effort have declined markedly. In 2003 the reported catch declined to around 390 tonnes from about 6,500 boat-days of effort. Reasons for the decline are unknown, but appear to be due, in part, to the response of the trawl fleet to the *Fisheries (East Coast Trawl) Management Plan 1999* that was introduced in January 2001.

For more background on the fishery, see Campbell *et al.* (2010, pp. 5-7).

4 Need

FRDC Project 2006/024, Harvest strategy evaluation to optimise the sustainability and value of the Queensland scallop fishery, evaluated a number of harvest strategies using an open-loop[i] simulation approach. This work was timely as it fed into the review process for the East Coast Otter Trawl fishery, of which the scallop fishery is a key component. While certain strategies consistently performed better than others in terms of the performance indices examined (catch per unit effort, biomass, total catch and economic value), the intra-scenario variation was very large in relation to the inter-scenario variation. That is, the simulation framework had low discriminating power in relation to the uncertainty (largely due to stock-recruitment) for any given scenario. To provide further support to the trawl plan review, currently in its final stages, this work was proposed to build on the modelling work begun in 2006/024. Specifically, there was a need to upgrade the framework to estimate maximum sustainable yield and other reference points, in a way that incorporated the spatial management of the fishery.

This project builds on previous work by completing the path to adoption of the recommendations contained in the 2006/024 report.

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[i] Harvest strategy evaluations are either closed-loop, or open-loop, depending on the presence or absence of feedbacks in the system. In closed-loop evaluations the position of a management lever (for example the total allowable catch) is adaptively set based on current conditions in the simulation (for example using a virtual stock assessment based on data ‘collected’ from the full model). In open-loop evaluations there is no such feedback, and the management strategy remains fixed for the duration of the forward projections.

5 Objectives

The objectives as stated in the proposal were:

1. Propose and construct a set of reference points for the scallop fishery (e.g., target and limit effort)
2. Test the reference points in the (already constructed) MSE framework, i.e., what levels for the reference points perform best in terms of the sustainability and profitability indicators

These objectives need some elaboration. The construction of reference points should perhaps read the estimation of reference points. The ‘already constructed MSE framework’ refers to the open-loop simulation framework developed in Campbell (2010). As discussed in the previous section this framework required modification to be suitable for the estimation of reference points and these modifications were the main focus of this work.

A refined and more detailed list of objectives is:

1. Re-cast the spatial recruitment parameters as spatial process errors (use a state-space approach).
2. Improve the spatial stratification of the model to improve the estimability of the spatial process error terms and the knowledge parameter.
3. Incorporate the long term standardised catch rate series to improve the contrast in the data and improve the estimability of the stock-recruitment parameters.
4. Construct a simulation component that generalizes the concept of maximum sustainable yield (and other reference points) to a spatial setting in a statistically robust fashion.

6 Methods

The estimation of reference points for a spatially complex fishery that relies on a system of rotating closures (areas of the ocean that are closed to fishing) for management is a challenging task. The best starting point in our opinion is the state-space approach to parameter estimation for population dynamics models (de Valpine 2002; Schnute 1994). The state-update equations for population dynamics include terms for both 'observation error', whereby we do not observe the state of the system exactly, and 'process error', whereby the model describes the system only approximately. A likelihood that involves only observation error could be calculated from the full likelihood by integration over all the process errors.

This project uses a Bayesian setting, in which probable values of all model parameters are simulated by Markov chain Monte Carlo (MCMC). In this setting the above integration is not necessary; output values for parameters relating to process error can be ignored if desired.

By modelling the spatial aspects of the fishery within a rigorous statistical framework, complex spatial management questions can be addressed in an absolute sense; i.e., quantities such as equilibrium reference points can be estimated. In that sense, our approach is more in line with traditional stock assessment, and contrasts with the Management Strategy Evaluation type framework, in which estimates of the relative performance of one strategy over another are the focus.

Section 6.1 details the population dynamics for the full spatial model. Because the history of the fishery is complex, and because data has become more plentiful over time, the full time series of the model features a number of different 'phases' during which different sets of parameters are active, different sets of data are fitted, and the model structure itself may be different. Explaining these different phases is the role of section 6.2. Sections 6.3 and 6.4 detail the likelihood terms that together form the objective function for parameter estimation. Section 6.3 details the likelihoods that are used to fit to the various data sources, and section 6.4 details the priors.

Parameter estimation proceeds in two phases: an initial optimisation over all parameters (including parameters relating to process error), followed by an MCMC routine to obtain a posterior for each parameter and enable the process error terms to be integrated out. This process is described in section 6.5, along with a description of the model variants that capture different assumptions. Section 6.6 explains the equilibrium simulation framework within which various management scenarios can be investigated and their impact assessed in terms of reference points. Three particular scenarios are investigated.

6.1 Population dynamics

The model is a spatially stratified state-space model with multiplicative log-normal process error and a range of observation-error structures depending on the type of observation. At time-step i, the expected number of scallop in cell k of age j is

$$N_{i,j,k} = \begin{cases} \Phi_{m(i)} R_{y(i),k} & \text{for } j = 1 \\ N_{i-1,j-1,k} e^{-Z_{i-1,j-1,k}} & \text{for } j = 2,\ldots,48 \end{cases} \qquad (1)$$

where the global time-step index i increments monthly, $y(i)$ maps the current time-step to fish-year, $m(i)$ maps the time-step to fish-month, $N_{i,j,*}$ is the number of scallop[ii] of age j at time i

[ii] a '*' in the subscript indicates the dimension is summed over.

summed over cells, $R_{y(i),k}$ is the total recruitment in the year corresponding to time-step i for cell k, $\Phi_{m(i)}$ is the proportion of annual recruitment allocated to month $m(i)$, and $Z_{i,j,k}$ is total mortality at time-step i, for scallop of age j and in cell k.

Fish-years start in November, so $m(i) \in 1..12$, where 1 is November and

$$y(i) = \begin{cases} y'(i)+1 & \text{if } m(i) \le 2 \\ y(i) & \text{if } m(i) > 2, \end{cases}$$

where $y'(i)$ is the mapping for calendar year (e.g., December of calendar year 1997 is fish-month 2 of fish-year 1998). From this point on we will drop the prefix ‘fish’ and all references to year and month should be taken to be fish-years and fish-months unless stated otherwise. We will also abuse notation to write $R_{y,k}$ as shorthand for $R_{y(i),k}$ and similarly with month ($m(i)$ □ m).

Recruitment is based on the flexible Deriso-Schnute three-parameter formulation which contains the Ricker, Beverton-Holt and Schaefer as special cases,

$$R = f(P) = \alpha P(1-\beta\delta P)^{1/\delta}$$

where R is recruitment, P is spawning stock size (in our case this is egg production), α is the ‘productivity’ parameter, β is the ‘optimality’ parameter and δ is the ‘recruitment limitation’ parameter (Schnute 1985). Specifically, the number of recruits, denoted $R_{y,k}$, in year y and cell k is given by

$$\log\left(\frac{R_{y,k}}{A_k / A_*}\right) = \log\left(\alpha P_{y-1}(1-\beta\delta P_{y-1})^{1/\delta}\right) + \xi_y + \psi_k \tag{2}$$

where A_k is the area of cell k, P_{y-1} is total egg production in the previous year, ξ_y is a temporal recruitment anomaly[iii], which is a random variable with prior distribution $\mathrm{N}\left(0,\sigma_\xi^2\right)$ and ψ_k is a spatial recruitment anomaly with prior distribution $\mathrm{N}\left(0,\sigma_\psi^2\right)$.

Egg production in year y is defined as

$$P_{y(i)} = \sum_{i'\in[i]}\sum_j\sum_k \omega_{m(i')} \frac{1-e^{-Z_{i',j,k}}}{Z_{i',j,k}} \frac{1}{2} N_{i',j,k} \mathrm{mat}_j \mathrm{fec}_j \tag{3}$$

where $\omega_{m(i')}$ is the proportion of annual egg production occurring in the month corresponding to time step i', $[i]$ is a “same-year” equivalence class on time-step i, mat_j is the proportion of scallop mature at age j and fec_j is the number of eggs produced by a scallop at age j.

The monthly recruitment proportion is given by

$$\Phi_m = \frac{\exp\left(\iota\cos(2\pi(m-\vartheta)/12)\right)}{2\pi I_0(\iota)} \tag{4}$$

where $I_0()$ is the modified Bessel function of order 0 and ι and ϑ are parameters to be estimated (Mardia and Jupp 2000).

The total mortality is

[iii] There are many names used for this variability in the population dynamics: process error, random effect, anomaly, deviate. They are all mathematically equivalent and will be used interchangeably.

$$Z_{i,j,k} = M + S_{i,j} F_{i,k} \quad (5)$$

where M is the instantaneous rate of natural mortality, assumed to be independent of age and time, $S_{i,j}$ is selectivity at time-step i and at age j, and $F_{i,k}$ is the instantaneous rate of fishing mortality that is applied to the selected scallops at time-step i in cell k. The fishing mortality is modelled as

$$F_{i,k} = \tilde{q}_k \, f_y \, E_{i,k} \quad (6)$$

where $\tilde{q}_k$ is the catchability in cell k, f_y is the fishing power multiplier (relative to 1989) in the year of month i, and $E_{i,k}$ is the effort allocated to cell k at time-step i.

Effort allocation is inspired by Ellis and Wang (2007). In their model the relationship between the spatial distribution of abundance and the spatial distribution of effort is taken to represent the degree of knowledge fishers have about the location of high density areas. This is quantified through a power relationship with exponent γ: if this exponent takes a value of one this implies effort is distributed spatially in proportion with abundance; a value greater than one implies an exaggerated intensity of effort in high abundance areas; a value less than one implies a flatter distribution approaching uniform in the limit of zero knowledge. Ellis and Wang's model was aimed at catch rate standardisation, whereas here we use it for effort allocation. Thus, predicted effort in cell k at time i is

$$E_{i,k} = \breve{E}_{i,*} \frac{(N_{i,*,k} / A_k)^{\gamma} A_k \Gamma_{i,k}}{\sum_{k'} (N_{i,*,k'} / A_{k'})^{\gamma} A_{k'} \Gamma_{i,k'}} \quad (7)$$

where A_k is the area of cell k (in km^2), $\breve{E}_{i,*}$ is the observed[iv] effort at time-step i summed over cells (in boat-nights), γ is the knowledge parameter (higher values of γ will provide more effort in higher density areas and result in higher catches), and $\Gamma_{i,k}$ is the closure operator (zero if cell k is closed to fishing at time-step i and one otherwise). In fact this knowledge parameter should perhaps be termed the 'remaining knowledge' parameter as some of the knowledge that relates to targeting will be already captured through the cpue standardisations. See section 9 for more discussion on this.

Ellis and Wang (2007) proposed a location-independent quantity termed the 'instantaneous' catchability, p, defined as the proportion of scallop within a local area that would be caught by applying one unit of effort per unit area, and related it to the 'spatial' catchability (proportion of scallop in the population caught by one unit of effort, which is location-dependent via the relative abundance). We follow a similar path. However, our spatial catchability is the proportion of scallop *in the cell* taken by one unit of effort, as opposed to the proportion of scallop in the total population. We assume that the density of scallop is constant within each cell. Thus the catchability in cell k is

$$\tilde{q}_k = \frac{pa}{A_k} \quad (8)$$

where A_k is the area of cell k, and a is a single unit of effort (required to balance the units). The definition of catchability for the whole fishery, $\bar{q} = C/(NE)$, is referred to as the 'average catchability' by Ellis and Wang (2007), although we prefer the term 'integrated catchability' as it is the whole-of-fishery catchability with space integrated out. Note the equation in the previous sentence was just a shorthand - the full equation for integrated catchability must be derived from the Baranov equation because the catch may amount to a substantial proportion of the population:

[iv] $\breve{x}$ indicates x is an observed quantity.

$$\bar{q}_i = \frac{.5\left(-(M-2)+\sqrt{(M-2)^2-8\dfrac{C_{i,*}}{\sum_j w_j S_{i,j} N_{i,j,*}}}\right)a}{f_y E_{i,*}} \tag{9}$$

The derivation of this equation is contained in section 17.1. The ratio of the integrated catchability to the instantaneous catchability is a measure of the relative impact of fish aggregation and fisher targeting on catchability, and is termed the catchability index: $\kappa_i = \bar{q}_i A/(pa)$ (A scales the instantaneous catch rate to the whole fishery and a is again required to balance units).

See for the list of all symbols used in this report.

6.2 Model phases

The population dynamics outlined above formed the basis of a spatial framework for investigating patchy (fine scale) distributions of scallop beds and their fishing mortality. Fine-scale spatial data was required to inform parameter estimation for the dynamics. This was achieved using VMS and fishery-independent data after year 2000. Prior to the introduction of VMS in 2000, spatial data was recorded only through logbooks at the ½ degree grid scale. In order to make the best use of the pre-2000 historical data sources (which can often be the most crucial for determining equilibrium quantities such as MSY), the model history was divided into a number of phases. The following aspects were used to define the phases:

- Annual catch for the fishery was reported in Dredge (2006) going back to 1956; however, the reliability of these records in the earlier years was unverified.
- As the long-term catch rate series goes back to 1978, it was decided to model catch removals starting from this point (actually from November 1977), with a prior 'warm-up' period of 25 years during which single fishing mortality value, F_{pre}, would be estimated against historical harvests reported by Dredge (1960).

For the time phase of unknown fishing effort, a number of parameters and assumptions were needed. Annual effort between 1978 and 1988 was modelled as a linear trend, parameterised in terms of total effort at two reference years, 1980 and 1985 (this improved stability of the parameter estimation). Monthly effort was assumed to follow a von Mises distribution (Equation (4)), with a further two parameters assigned. These parameters were initialised to the best fit of the known effort pattern during 1989-2003. The parameters covering 1978–1988 were estimated by fitting to annual total catch during this period from Dredge (2006), in addition to monthly standardised catch rates.

The standardised catch rates were modelled as two separate time series, one from 1977 to 2008 and the other from 1988 to 2009. The reason for this was the lack of reliable vessel characteristics and gear data pre-1988. The 1977-2008 standardisation used the following variables: hours fished, fish-year, month, CFish grid, prawn catch, lunar phase and boat mark (Campbell *et al.* 2010). The 1988-2008 standardisation in addition used gear characteristics such as horsepower, net size and presence of search assisting technology (e.g. GPS). For more details on the differences between the two standardisations see Campbell *et al.* (2010), and for details of the standardisation methodology see O'Neill and Leigh (2006). One of the main differences was that the longer-term standardised series, known hereafter as the 'long-term catch rate', was constructed from data that, prior to 1988, was collected from a voluntary logbook program. The catch rates during the early part of the series were high—almost an order of magnitude above current catch rates—and are probably due in part to the voluntary logbooks being maintained only by the best fishers. For this reason an alternative catchability coefficient was used for this period of the model.

Management changes through time were another key determinant of model phases. It was decided to introduce the full spatial structure in the model from 1997 (November 1996) which coincided with the introduction of spatial closures. For the precise history of the closures see section 15.1. Prior to the introduction of spatial structure in the model, a κ_{early} value is needed to link the early instantaneous fishing mortality to catchability because the cell structure upon which κ is defined is not present.

In summary, the additional parameters required to fit the model to historical data sources were

$$E_{1980}, E_{1985}, \iota_E, \vartheta_E, F_{pre}, p_{early}, \kappa_{early}$$

Table 1 summarises the model phases.

Table 1 Parameters sequentially switched on through model phases.

Phase	Main parameters switched on	Main parameters retired	Process errors switched on	Data fit to	Notes
No fishing, first 50 years	$\alpha, \beta, \delta, \iota, \vartheta$				Used to cycle model to unfished equilibrium
Warm-up fishing, 25 years	F_{pre}				Unknown fishing mortality
Fishing period 1: Nov 1977 to Oct 1988	$p_{early}, \kappa_{early}, E_{1980}, E_{1985}, \iota_E, \vartheta_E, \sigma_{\xi}$	F_{pre}	ξ	Long-term cpue; annual catch (Dredge)	Selectivity changes (see section 15.5)
Fishing period 2: Nov 1988 to Oct 1996	p	$p_{early}, E_{1980}, E_{1985}, \iota_E, \vartheta_E$		Long-term cpue; short-term cpue; annual catch (Cfish)	
Fishing period 3: Nov 1996 to Oct 2009	γ, σ_{ψ}	κ_{early}	ψ	Long-term cpue; short-term cpue; spatial catch and effort (Cfish and VMS); Spatial Survey (1997 – 2006)	Closures introduced

Table 2 Symbols used throughout the report. 'Type' indicates the whether the symbol is a parameter (P), data (D), derived quantity (V) or a function (F). Parameters are further divided into primary (P-P), process error (P-E) and nuisance (P-N)[v].

Symbol	Meaning	Unit	Where defined	Type
α	Stock-recruitment 'productivity' parameter	egg^{-1}	Before (2)	P-P
a	Unit of effort	boat-night	After (8)	-
A_k	Area of cell k	km^2	(7)	D
β	Stock-recruitment 'optimality' parameter	egg^{-1}	Before (2)	P-P
$C_{i,k}$	Predicted catch at end of time i in cell k	kg	(10)	V
$\breve{C}_{i,k}$	Observed catch at end of time i in cell k	kg	Before (11)	D
$\Gamma_{i,j}$	Closure operator	1	After (7)	D
γ	Knowledge parameter	1	Before (7)	P-P
δ	Stock-recruitment 'limitation' parameter	1	Before (2)	P-P
$E_{i,k}$	Effort in cell k at time-step i	boat-night	After (6)	D
E_{1980}	Annual effort in 1980	boat-night	Section 6.2	P-N
E_{1985}	Annual effort in 1985	boat-night	Section 6.2	P-N
${}^{p}\breve{E}_{i,k'}^{vms}$	Observed effort (VMS) in cell k' at time i as proportion	1	After (14)	D
fec_j	Fecundity at age j	egg	After (3)	D
f_i	Fishing power multiplier at time i	1	After (6)	D
$F_{i,k}$	Fishing mortality for scallop in cell k at time-step i	month^{-1}	(6)	V
F_{pre}	Fishing mortality prior to 1978	month^{-1}	Section 6.2	P-N
ι	von-Mises measure of concentration - recruitment pattern	month^{-2}	After (4)	P-P
ι_E	Von-Mises l measure of concentration - effort pattern pre-1989	month^{-2}	Section 6.2	P-N
M	Natural mortality	month^{-1}	After (5)	D
mat_j	Maturity at age j	1	After (3)	D
$N_{i,j,k}$	Number of scallop of age j in cell k at time-step i	1	(1)	V
$n_{E_{VMS}}$	Effective sample size for the VMS multinomial likelihood	1	After (14)	D
ξ_y	Temporal recruitment anomaly for year y	1	After (2)	P-E
κ_i	Catchability index at time-step i	boat-night km^{-2}	After (8)	V
κ_{early}	Catchability index prior to November 1996	boat-night km^{-2}	Section 6.2	P-N
p	Instantaneous catchability	km^2	After (8)	P-P
p_{early}	Instantaneous catchability prior to November 1989	km^2	Section 6.2	P-N

[v] Nuisance parameters are defined as those not used in the equilibrium simulations; see section 6.6.

P_y	Egg production in year y	egg	(3)	V
$\Phi_{m(i)}$	Monthly recruitment proportion in month of time step i	1	(4)	V
$\bar{q}_i$	Integrated catchability: proportion of population caught by one unit of effort at time i	1	(9)	V
$\tilde{q}_k$	Cell catchability: proportion of population in cell k caught by one unit of effort	1	(8)	V
$R_{y,k}$	Annual recruitment (number of one month old scallops) in cell k for year y	1	(2)	V
$\hat{R}_{y,k}$	Predicted 'recruitment': index of zero-plus scallop in October of year y, cell k	1	(18)	V
$\breve{R}_{y,k}$	Observed (survey) index of recruitment for year y and cell k	1	After (19)	D
$S_{i,j}$	Selectivity of scallop of age j at time i	1	After (5)	D
σ_ψ^2	Spatial recruitment process error variance	1	After (2)	P-N
$\sigma_\xi{}^2$	Temporal recruitment process error variance	1	After (2)	P-N
$\sigma_C{}^2$	Annual catch fitting variance	1	After (13)	P-N
$\sigma_{u1}{}^2$	Long-term cpue fitting variance	1	After (16)	P-N
$\sigma_{u2}{}^2$	Cfish cpue fitting varaince	1	After (17)	P-N
$\sigma_{Cs}{}^2$	Spatial catch (Cfish) fitting variance	1	After (11)	P-N
$\sigma_{Es}{}^2$	Spatial effort (Cfish) fitting variance	1	After (12)	P-N
u_i	Catch per unit effort at time i in cell k	kg boat-night^{-1}	(15)	V
$\breve{u}_i$	Observed (standardised) catch per unit effort at time i	baskets boat-night^{-1}	After (16)	D
$\upsilon_{m(i)}$	Kilograms per basket conversion factor for month of time i	kg basket^{-1}	After (16)	D
ϑ	von Mises distribution measure of location – recruitment pattern	month	After (4)	P-P
ϑ_E	von Mises distribution measure of location – early effort	month	Section 6.2	P-N
$\omega_{m(i)}$	Proportion of annual egg production in month of time i	1	After (3)	D
w_j	Average weight of scallop of age j	1	After (10)	D
ψ_k	Spatial recruitment anomaly in cell k	1	After (2)	P-E
$Z_{i,j,k}$	Total mortality for scallop of age j in cell k	1	After (5)	V

6.3 Data likelihoods

The predicted catch from the model during time-step i in cell k is given by

$$C_{i,k} = \sum_j \left(\frac{S_{i,j} F_{i,k}}{Z_{i,j,k}} w_j N_{i,j,k} \left(1 - \exp\left(-Z_{i,j,k}\right)\right) \right) \tag{10}$$

where $Z_{i,j,k} = S_{i,j} F_{i,k} + M$ is the total mortality in cell k at time i for scallop of age j, and w_j is the average weight (in kilograms) of scallop at age j. In order to fit to Cfish data which are aggregated at the grid-square level (see section 15.1) the cell index was mapped to its grid index using a sum operation (that is, cells in the same grid were summed), denoted $C_{i,g}$:

This was fitted to observed Cfish catch $\breve{C}_{i,g}$ with the –2 log-likelihood

$$L_{Cs-Cfish} = \sum_i \sum_g \left\{ \log\left(\sigma_{Cs}^2\right) + \frac{\left(\log(C_{i,g}) - \log(\breve{C}_{i,g})\right)^2}{\sigma_{Cs}^2} \right\} \tag{11}$$

where σ_{Cs} is a parameter to be estimated, and $L_{Cs-Cfish}$ implies the –2 log likelihood for spatial catch from the Cfish database. Similarly, model-predicted effort was fitted to Cfish data using

$$L_{Es-Cfish} = \sum_i \sum_g \left\{ \log\left(\sigma_{Es}^2\right) + \frac{\left(\log(E_{i,g}) - \log(\breve{E}_{i,g})\right)^2}{\sigma_{Es}^2} \right\} \tag{12}$$

Prior to the spatial phase of the model (prior to November 1996) the model was fitted to a time-series of annual total catch composed from the Dredge data between 1978 and 1988, and the Cfish data between 1989 and 1996. The –2 log likelihood was

$$L_C = \sum_y \left\{ \log\left(\sigma_C^2\right) + \frac{\left(\log(C_{y,*}) - \log(\breve{C}_y^{\#})\right)^2}{\sigma_C^2} \right\} \tag{13}$$

where σ_C is a parameter to be estimated, $\breve{C}_y^{\#}$ is the model predicted annual total (summed over months and cells), and $\breve{C}_y^{\#}$ is the observed series (composed of Dredge and CFish).

Starting in December 2000 and going through to December 2006 the model was also fitted to high-resolution effort information from the VMS dataset created using the Trackmapper software. See Good *et al.* (2007, pp. 20-77) for details on how fine-scale catch and effort were derived from Cfish data and vessel track (location) information. It was considered unnecessary and perhaps unwise to fit to fine-scale catch in addition to effort, because the procedures that disaggregate the catch spatially involve riskier assumptions than the estimation of effort. Future work should look at this issue in more detail (see section 7). The VMS data provided information at the cell level (as opposed to just the grid-square level from Cfish). VMS data was not available after December 2006 and for grid-squares corresponding to cells 42 and 43, as these locations were considered to be outside the bounds of the fishery when the VMS routines were run[vi]. Total effort from the VMS data set was also not considered to be as reliable as the totals from Cfish, so the aim was to fit only the relative variation across space and time. This was done using a multinomial formulation

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[vi] due to an oversight in the original VMS data extraction during project 2006/024, the catches for cells 42 and 43 were not available as they were west of the western boundary of the trackmapper target area; due to the time required to re-extract the VMS data set, and given that their total catch was tiny in proportion to the overall catch, and that the spatial data from the Cfish logbooks made their combined total redundant, this was not revised. Updating the series past December 2006 also was not attempted due to limited personnel resources.

$$L_{E_{VMS}} = -2\sum_{k'\in K}\sum_{i'\in I} n_{E_{VMS}}\ {}^{p}\breve{E}_{i',k'}^{vms} \log {}^{p}E_{i',k'} \tag{14}$$

where $n_{E_{VMS}}$ is the effective sample size (set in an ad hoc fashion, see section 7), ${}^{p}\breve{E}_{i,k'}^{vms}$ is the observed VMS effort in cell k' at time i' as a proportion of total effort (summed over space and the entire time period), ${}^{p}E_{i',k'}$ is the model predicted effort for cell k' at time i' as a proportion, K is the set of valid spatial indices (all excluding cells 42 and 43) and I is the set of valid temporal indices (December 2000 – December 2006 inclusive).

Catch per unit effort (cpue) during time step i was predicted as

$$u_i = \frac{\sum_k C_{i,k}}{f_i \breve{E}_{i,*}} \tag{15}$$

This was fitted to the two standardised cpue series. First, the long-term cpue series was fitted using

$$L_{u1} = \sum_{i\in U_1}\left\{\log\left(\sigma_{u_1}^2\right) + \frac{\left(\log(u_i) - \log(\breve{u}_i^1)\right)^2}{\sigma_{u_1}^2}\right\} \tag{16}$$

where U_1 indexes the valid months for the series (November 1977 to October 2008, omitting the months of October from 2001 onwards where the fishery was closed), $\breve{u}_i^1 = \hat{u}_i^1 / \upsilon_{m(i)}$ is the standardised long-term cpue in kilograms per boat-night, $\hat{u}_i^1$ is the standardised cpue in baskets per boat-night, and $\upsilon_{m(i)}$ is the kilograms per basket conversion factor for the month corresponding to time-step i. Similarly the Cfish cpue series was fitted using

$$L_{u2} = \sum_{i\in U_2}\left\{\log\left(\sigma_{u_2}^2\right) + \frac{\left(\log(u_i) - \log(\breve{u}_i^2)\right)^2}{\sigma_{u_2}^2}\right\} \tag{17}$$

where U_2 indexes November 1998 to October 2009 (omitting October from 2001 on).

Let τ be a vector of indices that identify the month of October in the overall temporal index, i.e., $\tau = \{12, 24, \ldots\}$. Then

$$\hat{R}_{i,k} = \log\left(\sum_{j=2}^{6} N_{(\tau(i),j,k)}\right) \tag{18}$$

and the likelihood for the survey data was

$$L_R = \sum_i \sum_k \left\{\log(\sigma_R^2) + \frac{1}{\sigma_R^2}\left(\log(\breve{R}_{i,k}) - \log(\hat{R}_{i,k})\right)^2\right\} \tag{19}$$

where $\breve{R}_{i,k}$ is a (scaled) index of abundance of zero-plus scallop (shell height less than 78mm) in the month of October for year i and cell k.

See table Table 3 for a summary of the data sample sizes for each of these likelihoods.

Table 3 Data summary used in model fitting.

Data	L_{u1}	L_{u2}	L_C	L_ξ	L_ψ	$L_{EsCfish}$	$L_{CsCfish}$	L_{Evms}	L_R
Granularity	Month	Month	Year	Year	Cell	Month x Grid	Month x Grid	Month x Cell	Month x Cell
Period/Range	Nov 1977 to Oct 2007	Nov 1988 to Oct 2009	1978 to 1988	1978 to 2009	All cells	Nov 1989 to Oct 2009	Nov 1989 to Oct 2009	Dec 2000 to Dec 2006	Oct of 1997-2006, partial spatial coverage; see
Sample size	360	262	11	32	43	156 x 19	156 x 19	73 x 41	309

6.4 Specification of priors

Generally the priors were designed to be as non-informative as possible, with the exception of the recruitment limitation parameter δ, which was constrained to sit between a Beverton Holt curve at one end, and a Ricker curve at the other. Flat priors were usually provided with ‘sanity’ bounds to prevent the optimisation algorithms from causing the model to produce infinities or divisions by zero.

6.4.1 Priors on σ_ξ^2 and σ_ψ^2

The variances for the process error terms were given flat priors on the log scale. Sanity bounds: [-6,5].

6.4.2 Prior on α and β

The productivity and optimality parameters of the stock-recruitment relationship were given flat priors. Sanity bounds: [1, 500] and [0.00000001, 50] respectively.

6.4.3 Prior on δ

The recruitment limitation parameter of the stock-recruitment relationship was uniform between -.999999999 (Beverton-Holt) and -.000000001 (Ricker). See (Schnute 1985, pp. 418-419) for examples of the curves this range produces.

6.4.4 Prior on γ

The knowledge parameter was given a flat prior on the log scale. Sanity bounds [-3, 3].

6.4.5 Priors on p and p_{early}

The instantaneous catchability terms were given flat priors on the log scale. Sanity bounds [-6, 6].

6.4.6 Prior on $\iota, \vartheta, \iota_E$ and ϑ_E

The von-Mises parameters for the inter-annual recruitment pattern and the pre-1988 inter-annual effort pattern were given flat priors with no sanity bounds.

6.4.7 Priors on E_{1980} and E_{1985}

The annual total effort for reference years 1980 and 1985 were given flat priors with sanity bounds [1, 50000].

6.4.8 Prior on F_{pre}

The pre-1978 fishing mortality was uniform [1e–6, 0.2].

6.4.9 Priors on $\sigma_{Cs}, \sigma_{Es}, \sigma_C, \sigma_{u1}, \sigma_{u2}$ and σ_R

These nuisance parameters were given flat priors without bounds. $\sigma_C, \sigma_{u1}, \sigma_{u2}$ and σ_R were profiled out (replaced with analytically derived values equal to the sample standard deviation).

6.4.10 Prior on ξ_y

The –2 log-likelihood prior for the temporal anomalies was

$$L_\xi = \sum_y \log(\sigma_\xi^2) + \frac{\xi_y^2}{\sigma_\xi^2} \tag{20}$$

with sanity bounds on the ξ_y of [–5, 5].

6.4.11 Prior on ψ_y

The –2 log likelihood prior for the spatial anomalies was

$$L_\psi = \sum_y \log(\sigma_\psi^2) + \frac{\psi_y^2}{\sigma_\psi^2} \tag{21}$$

with sanity bounds on the ψ_y of [–5, 5].

6.5 Parameter estimation and model variants

Parameter estimation proceeds in two phases – an initial gradient descent procedure, followed by a Monte-Carlo Markov Chain (MCMC) routine to generate the full posterior distribution for each parameter (including process errors). Both phases were conducted using AD Model Builder (ADMB Project 2009). AD Model Builder uses automatic differentiation to compute the gradient of the objective function, which leads to more stable optimization than methods that don't employ exact gradients (especially in a high number of dimensions). Once parameter estimation finishes, the Hessian (the second order partial derivatives of the objective function at the minimum) is available to be used to produce an (almost) multivariate normal distribution for the jumps of the Metropolis-Hastings algorithm (Hastings 1970; Metropolis *et al.* 1953), the MCMC algorithm used in the second phase. The distribution is not exactly multivariate normal because the random vectors produced are modified to satisfy any bounds on the parameters. The idea is that MCMC produces a posterior for all parameters, and the process error parameters can then be 'integrated out' by projecting the full posterior distribution onto the subspace corresponding to the primary parameters.

In the first phase we obtained all parameter estimates by minimising a weighted sum of the above –2 log likelihoods:

$$L_{total} = w_\xi L_\xi + w_\chi L_\chi + w_{Cs} L_{Cs-Cfish} + w_{Es} L_{Es-Cfish} + w_C L_C + L_{Evms} + w_{u1} L_{u1} + w_{u2} L_{u2} + w_R L_R \tag{22}$$

As noted by Francis (2011), explicit data weighting is often required when combining multiple data sources, and this is not necessarily able to be done in a purely objective fashion (some subjective input may be required). Weights were assigned by trial and error using the guiding principles that the optimisation must produce

- a good fit to both of the catch rate series,
- a reasonable fit to the total catch series,

- stable and sensible variances for the process errors.

Minimal adjustments to the 'natural' weighting (i.e., w = 1) were used given the above; weights used are given in Table 5.

In order to cover some of the many possible assumptions on historical data four variant models were investigated:

1. Model one used only the long-term catch rate data, and assumed that it was an accurate indicator of relative abundance through time. Thus in this model p_{early} was set to the estimated value for p. Effort levels in 1980 and 1985 were able to be estimated with reasonable precision (estimated standard deviation not too high) in this case. Exploratory model runs suggested that there was a strong confounding between the knowledge parameter, γ, and the magnitude of the spatial recruitment anomalies, governed by σ_{ψ}. Thus in all models reported here γ was fixed, and different values were tried as sensitivity tests, using further exploratory model runs to guide these choices (when σ_{ψ} is fixed, γ can be estimated). Finally, exploratory runs also indicated that F_{pre} was always estimated at its lower bound (1e–6), δ was always at its lower bound (–.99999; i.e. Beverton-Holt), and ι_E was unstable. F_{pre} and δ were therefore fixed (for all models) at these lower bounds, and ι_E was fixed at the value corresponding to the effort pattern during the first five years of the Cfish data (0.81).
2. Model two considered the voluntary log-book phase of the long-term catch rate series to possibly correspond to a more efficient subset of the fleet, and thus p_{early} was estimated. Initial model runs suggested that with the extra degree of freedom introduced by p_{early}, effort in the early years became quite unstable and would often blow up to unreasonable values. There were a number of possible sources for this indeterminacy and model two was aimed at providing a baseline model to control this via three simplifications. Firstly, effort in the early years was fixed at 'reasonable' guesses. Secondly, the standard deviations on the process errors were fixed for this run. Finally, the likelihood for the survey recruitment index was dropped for this model.
3. Model three was an attempt to relax some of the assumptions of model two: E_{1980} was estimated, and both process error variances were also estimated.
4. Model four considered a higher value of the knowledge parameter: $\gamma = 2$, compared to the models two and three which used a value of 1.65, but the same as in model one. The recruitment index likelihood was reinstated. Finally, effort in the early reference years was fixed, but at new values obtained via an intermediate model which estimated these parameters only, keeping other parameters fixed.

In summary, there are two hypotheses on the long-term catch rate series: it is valid as a single series, or it should be considered piecewise, with a different catchability on the early years. Model one deals with the first case. Models two through four attempt to cover a few of the different assumptions required to deal with the extra degrees of freedom introduced by attempting to estimate a second catchability for this early period. They also investigate sensitivity to the magnitude of the knowledge parameter, the magnitude of process error variance, and the influence of the recruitment survey index. Table 4 summarises the different parameters used in these model variants, and Table 5 the different likelihood weightings.

Table 4 Summary of parameters estimated in the model variants.

	Primary	Process error	Nuisance	Total
Model One	$\alpha, \beta, \delta, \iota, \vartheta, p$	ξ_y, ψ_k	$\sigma_\psi, E_{1980}, E_{1985}, \kappa_{early}, \vartheta_E$	85
Model Two	$\alpha, \beta, \delta, \iota, \vartheta, p$	ξ_y, ψ_k	$p_{early}, \kappa_{early}, \vartheta_E$	83
Model Three	$\alpha, \beta, \delta, \iota, \vartheta, p$	ξ_y, ψ_k	$\sigma_\xi, \sigma_\psi, p_{early}, E_{1980}, \kappa_{early}$	86
Model Four	$\alpha, \beta, \delta, \iota, \vartheta, p$	ξ_y, ψ_k	$\sigma_\psi, p_{early}, \kappa_{early}, \vartheta_E$	84

Table 5 Likelihood weightings used across the model variants.

Model	L_{u1}	L_{u2}	L_C	L_ξ	L_ψ	$L_{EsCfish}$	$L_{CsCfish}$	L_{Evms}	L_R
One	.75	-	1	1	.1	.005	.0001	1	.05
Two	.75	1	1	1	.2	.005	.0001	1	-
Three	.75	1	1	1	.2	.005	.0001	1	-
Four	.75	1	1	1	.2	.005	.0001	1	.05

6.6 Equilibrium simulations for management scenarios

Equilibrium simulations were conducted using the following procedure. First, choices are made regarding the equilibrium selectivity (based on minimum legal size), closure schedule, fishing power trend, knowledge parameter and monthly effort pattern. Then:

1. A sample is drawn from the full multivariate posterior (including process errors).
2. The model is run from beginning (25 years prior to 1978) to end (October 2009) according to the equations given in section 6.1.
3. A value of annual effort is chosen.
4. From November 2009, a ‘forward-projection’ model takes over which has no recruitment variation, but which continues with the spatial recruitment effects taken from the posterior, has fishing mortality calculated according to the combination of the chosen annual effort, the fixed effort pattern and knowledge parameter, and is otherwise identical to the model operating in the final phase (1997 to 2009).
5. Run this model for a fixed number of years, n_f, where n_f will be an integer multiple of the closure schedule period, n_c (e.g. if the closures repeat their pattern every 2 years this will be 2).
6. Calculate the average total annual catch over the last n_c years.
7. Return to step 3 and choose a new value of effort until the annual catch is maximised.
8. Return to step 1.

In this way we generate a distribution over the maximum sustainable yield (MSY) and the corresponding annual effort (Emsy). By themselves these indicators are insufficient to explore some questions relating to spatial management. In particular the objective of the rotating spatial closures is not only sustainability of the stock: they are also aimed at increasing the efficiency of the fleet in terms of catch rates, and hence profitability. To obtain an indicator of the impact on catch rates, it is not appropriate to simply consider yield per unit effort at MSY: more effort will be used as long as it increases yield, regardless of the potentially diminishing returns in additional yield for every additional boat-night. Instead we want an indicator of *how much of that yield was taken at high catch rates*. Thus the proposed indicator is constructed as follows:

1. Calculate the mean catch rate (in kg of meat weight per boat night) across all months and cells for the last n_c years of the forward simulation.
2. Calculate the catch during this period that was taken above this mean catch rate value.
3. Divide this catch at high catch rates by the MSY.

This indicator is termed $Y_{u>u*}$.

There were three management scenarios considered across two management 'levers' – minimum legal size and spatial closures.

The first scenario was the current system ('status quo'): 90mm year-round MLS (this is status quo in terms of what was currently in use in 2010 and 2011, which is different from 2009 and thus different from the last year of the model) and closures:

- rotating on a 2 year schedule with 15 months closed and 9 months open
- openings beginning in January
- six closures in total, two for each of the three main high density zones (see Figure 1)
    - cells 2 through 9 being the first zone, known as 'Hervey Bay'
        - cells 2 through 5 being first closure, 6 through 9 the second
    - cells 11 through 18 being the second zone, known as 'Bustard Head'
        - cells 11 through 14 the third closure, 15 to 18 the fourth
    - cells 22 through 28 and cell 43 being the third zone, known as 'Yeppoon'
        - cells 22 through 24 plus 43 being the fifth closure, 25 through 28 being the sixth
- openings staggered for each latitudinal zone so that one of the two closed regions in that zone opens in January of every year

Scenario two considered a change back to the selectivity used in 2009 which was 90mm November to April, and 95mm May to October. Closures remained as status quo.

Scenario three used the scenario two MLS and change the closures to:

- rotating on a 3 year schedule with 33 months closed and 3 months open
- openings beginning in January
- nine closures in total, three for each of the three zones:
    - zone one:
        - cells 2 through 4
        - cells 5 through 7
        - cells 8 and 9
    - zone two
        - cells 11 through 13
        - cells 14 through 16
        - cells 17 and 18
    - zone three
        - cells 43 and 23
        - cells 22 and 24
        - cells 25 through 28
- openings staggered for each zone so that one of the three closed regions opens in January of every year

For scenarios one and two the intra-annual (monthly) effort pattern was set based on 2009 observed effort. For scenario three this was modified to better reflect the more pulse-like fishery that would occur with these shorter opening times. This modified pattern was constructed by multiplying the fraction of effort during the first three months (estimated from the 2009 observations) by 3, and then renormalising. The effort patterns are given in Table 6.

Table 6 Intra-annual (monthly) effort pattern across the scenarios.

	Nov	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
1 & 2	0.190	0.121	0.18	0.11	0.074	0.053	0.051	0.043	0.05	0.071	0.052	0.003
3	0.287	0.184	0.273	0.056	0.038	0.027	0.025	0.022	0.025	0.036	0.026	0.002

Equilibrium simulating settings across the three scenarios are summarised in Table 7.

Table 7 Equilibrium simulation settings for MLS, closures, effort pattern, fishing power and knowledge.

	Scenario		
	1	2	3
Minimum legal size	90mm year round	90mm Nov-Apr, 95mm May-Oct	90mm Nov-Apr, 95mm May-Oct
Closure schedule	Status quo: 9 months open starting in Jan, 15 months closed	Status quo: 9 months open starting in Jan, 15 months closed	3 months open starting in Jan, 33 months closed
Effort pattern	Fixed to 2009	Fixed to 2009	Modified – see Table 6
Fishing power	Fixed at 1.165	Fixed at 1.165	Fixed at 1.165
Knowledge parameter	Fixed at 1997-2009 value	Fixed at 1997-2009 value	Fixed at 1997-2009 Value
n_f	40	40	42
n_c	2	2	3

7 Results/Discussion

Point estimates for each parameter (output from phase 1 of parameter estimation) across the four models are given in Table 8, along with their associated standard errors. Goodness of fit statistics for the models are given in section 16.1. For the two catch rate series, model fit is reasonably good across all models (in the case of model one the fit is only to the long-term catch). In the case of annual catch, model fit is better when effort in the early reference years (1980 and 1985) is estimated, which is unsurprising. The resulting stock status, indicated by the relative egg production plots in section 16.2, is dramatically different between model one and models two through four, which is also not surprising, although the magnitude of the difference is striking. Model one puts egg production at 27% of 1977 levels, whereas models two through four put it anywhere between 40% and 70%. These two divergent outcomes correspond to two hypotheses on the stock-recruitment function: a very large stock with limited productivity (model one), or a smaller stock with increasingly greater productivity (models two through four). This is reflected in the alpha and beta parameter estimates. Model one has a relatively low alpha (productivity parameter), around 3, and a small beta (implying a large stock; beta is inversely proportional to stock size), whereas models two through four have alphas of 4.1, 7.7 and 11.6 respectively, implying increasingly productive stocks, with corresponding high (small stock size) betas.

There appears to be little in the goodness of fit plots, by themselves, to point clearly in the direction of one hypothesis or the other. However, one notable feature of the annual catch fit in the case of models two through four is the consistent underestimate of catch over the last 7 or 8 years. This is probably a result of the large drop in effort in 2002 onwards. Total annual effort averaged well over 10,000 boat nights in the period 1990 to 2001, compared to an average of not much over 5000 in the years since, leading to weaker vessels leaving the fleet. The consequent increase in fishing power may have exceeded that inferred by the catch rate analysis. Model one fits the annual catch more closely during this period, particularly in the last couple of years. This is primarily because this model does not fit to the Cfish-only catch rate series, and the long-term catch rate series only goes through to 2007. The model is therefore freer to increase stock size towards the end of the series, via a combination of the overall stock status (based primarily on stock-recruitment parameters and catch history) and recruitment anomalies. This can be seen clearly in Figure 9 in the mismatch between the Cfish catch rates and model predicted catch rate in the last two years.

Equilibrium simulation results are given in Table 9. Estimates of MSY are relatively robust to the assumptions on model inputs, with the maximum likelihood estimate of MSY ranging between 513 and 763 tonnes across the models. Emsy however varies widely, with a big jump from around 1,600 boat nights in the case of model one, to around 5,500 nights for model two, and then further big jumps to around 20,000 nights for model three and 35,000 for model four. This situation where the MSY estimates are relatively insensitive to model assumptions, but the Emsy estimates are very sensitive, is due to the fact that different hypotheses on stock status. A large, less productive stock and a smaller, highly productive stock lead to similar yields, but using different mechanisms to get there. In the case of the large, unproductive stock, MSY occurs at low fishing pressure to ensure that recruitment is high. For the small, highly productive stock, large recruitment still occurs at much higher effort levels; the MSY strategy is to fish hard to get the most out of the small stock and without having to worry about harming recruitment.

Table 8 Estimates and estimated standard deviation for the primary parameters. [a] For the random effect parameters the sample standard deviation is given. [b] These parameters were fixed: F_{pre} was fixed for all runs at 1e-6 and ι_E was fixed at 0.81; see section 6.5.

		α	β	ι	ϑ	log p	ξ [a]	log σ_ξ	ψ [a]	log σ_ψ	log γ	ϑ_E	κ_{early}	log p_{early}	E_{1980}	E_{1985}	h	E_{ratio}
Model	Est.	2.91	0.036	2.73	5.45	-0.86	0.39	-0.98[b]	1.09	0.075	0.69[b]	-4.7	1.40	-	3298	7499	0.23	0.27
One	Std. dev.	0.18	0.02	0.36	0.01	0.17	-	-		0.25	-	1.6	0.24	-	212	527	0.017	0.06
Model	Est.	4.12	0.27	2.64	5.89	-0.53	0.33	-1.5[b]	0.68	-1.0[b]	0.5[b]	0.027	1.2	0.14	5000[b]	4555[b]	0.30	0.43
Two	Std. dev.	0.62	0.15	0.29	0.18	0.096	-	-	-	-	-	0.96	0.15	0.21	-	-	0.032	0.098
Model	Est.	7.71	1.37	2.71	5.90	-0.59	0.40	-0.92	0.78	-0.26	0.5[b]	5.90	1.17	0.74	2469	4555[b]	0.46	0.70
Three	Std. dev.	3.25	0.97	0.29	0.14	0.11	-	0.10	-	0.27	-	0.48	0.16	0.19	177	-	0.11	0.11
Model	Est.	11.64	2.79	2.03	5.53	-0.53	0.38	-0.98[b]	0.97	-0.046	0.69[b]	-0.77	1.21	0.78	2907[b]	6319[b]	0.55	0.64
Four	Std dev.	7.17	2.48	0.17	0.09	0.15	-	-	-	0.19	-	0.43	0.17	0.19	-	-	0.15	0.095

Table 9 Reference point quantities across the four model variants and three management scenarios. Maximum sustainable yield (MSY) is in units of tonnes meat weight. Effort at MSY is in boat nights. The distribution from which the 50th, 5th and 95th percentiles are taken was generated using the procedure outlined in section 6.6, and should be considered illustrative only; see the final paragraph of that section. The mode (the point estimate from phase 1 of parameter estimation) is therefore particularly important. Y>u* indicates the fraction of MSY taken above an 'average' catch rate; see previous section for details. [a]The maximum allowed effort in these optimisation runs was 50000 boat nights so in this case the actual value is unknown, but greater than this.

		MSY				Emsy				$Y_{u>u^*}$			
Model	Scenario	Mode	50th	5th	95th	Mode	50th	5th	95th	Mode	50th	5th	95th
One	1	513	546	463	628	1681	1731	1088	2582	0.88	0.93	0.88	0.97
	2	518	551	466	633	1733	1779	1115	2643	0.89	0.93	0.88	0.97
	3	527	550	464	630	1853	1879	1190	2733	0.93	0.96	0.93	0.98
Two	1	547	571	506	670	5679	7435	3149	16228	0.71	0.85	0.79	0.91
	2	555	577	512	681	5886	7756	3251	17203	0.77	0.85	0.80	0.90
	3	556	580	512	683	5932	7829	3325	17385	0.86	0.91	0.87	0.94
Three	1	651	722	588	828	19238	28669	12821	46261	0.80	0.95	0.89	0.97
	2	661	734	597	842	20388	31163	13597	50000[a]	0.83	0.95	0.88	0.97
	3	662	735	598	838	21215	33723	14305	50000[a]	0.89	0.96	0.93	0.98
Four	1	745	756	703	809	34257	31903	23727	52302	0.81	0.89	0.86	0.91
	2	760	768	715	827	39746	35052	25789	59543	0.82	0.88	0.86	0.90
	3	763	771	718	827	53320	40410	28082	74989	0.86	0.94	0.77	0.97

Given this large variation in Emsy, most of the range of which appears to be outside the realm of sensibility, it is more appropriate to work backwards from MSY, via target catch rates, to arrive at sustainable effort levels. For example an MSY of 500 t, with an average catch rate of 100 kg per boat night, corresponds to an annual effort of 5000 boat nights.

It is instructive to compare these estimates with previous estimates reported in O'Neill *et al.* (2005), and reproduced in Table 10. In particular scenario one is comparable to the 90 mm year round, Beverton-Holt results: the MSY from the earlier work is at the upper end of our results, and this is probably largely due to that work not using the pre-Cfish / voluntary catch rate data (which leads to more pessimistic results).

Table 10 Equilibrium reference points reported in O'Neill *et al.* (2005)

	Beverton-Holt		Ricker	
	MSY	Emsy	MSY	Emsy
Size limit – 90mm all year	650 (129:1895)	12287 (4852:35668)	590 (68:1679)	8853 (3190:18790)
Size limit – Nov-Apr 90mm, May-Oct 95mm	653 (130:1910)	11254 (4552:31182)	592 (68:1695)	9123 (3273:19571)

In terms of variation in the reference points across scenarios, the 95 mm MLS in winter is only marginally better than 90 mm year round, and there is essentially no further improvement to MSY offered by the change to a three-year, pulse like closure schedule. It is however more instructive to consider the third equilibrium quantity, $Y_{u>u^*}$, for understanding the impact of the change to the closures. As discussed in 6.6, $Y_{u>u^*}$ is the portion of the MSY taken at above the average catch rate. A higher value indicates a more pulse-like fishery where more catch can be taken at higher values. A more comprehensive approach would be to consider MSY when catch is not removed unless above a certain threshold, however the $Y_{u>u^*}$ statistic is a useful proxy. The value of this indicator does increase for scenario 3: 21% over scenario 1 and 12% over scenario 2 in the case of model two.

Both the parameter estimation and the equilibrium simulations are relatively computationally demanding, with phase one (optimisation) of estimation taking roughly 20 min, phase 2 (MCMC) taking roughly 48 hours for 1,000,000 iterations, and the equilibrium simulations taking roughly 1 minute for every draw from the MCMC posterior[vii]. The number of MCMC iterates run and the number of equilibrium simulations performed are given in Table 11. Note that for models one, three and four the numbers of MCMC iterations completed were small, relative to the complexity of the problem, and this is borne out by the obvious non-stationarity in these MCMC output plots (section 16.4), particularly in models 3 and 4. For this reason the results based on the MCMC chain (the quantiles of the distribution) for models one, three and four should be considered illustrative only. Model two was run for far longer, but the presence of a second mode at higher values of alpha (see Figure 30) indicates that the solution surface is complex, and the fact that this mode was only explored for a single relatively short period in 1,297,800 iterations indicates that at least tens of millions of iterations would be required to pass the usual convergence tests.

Table 11 Sample size statistics for MCMC and the equilibrium simulations. [a]Not all saved MCMC samples were run through the equilibrium simulations; 'every' here indicates how the saved samples were further sub-sampled for the simulations – e.g. in the case of model three 119500 iterations were completed with every 10th saved, and of these saved values 100 were sub-sampled starting from the first sample and taking every 10th out to 1000.

	Model One	Model Two	Model Three	Model Four
MCMC iterations	148900	1297800	119500	100900
Saved every	10th	10th	10th	10th
Equilibrium simulations	100	300	100	50
Sub-sampled every[a]	10th	40th	10th	10th

[vii] using a Dell workstation with Intel Xeon X5355 processor @ 2.66 GHz, 4Mb cache, and 16 Gb of RAM.

8 Benefits and adoption

The beneficiaries of the research are the saucer scallop industry and fisheries management within the Department of Employment, Economic Development and Innovation (DEEDI), Queensland. The research provided a number of benefits and updated our understanding of saucer scallop spatial dynamics. The stock analyses have updated harvest recommendations and clarified size limit and spatial closures options for review of the trawl plan. The research has provided opportunity for increased industry confidence and understanding this spatially complex fishery.

It is difficult to quantify the benefits of the research in terms of price or value of the yield. However, from this science the adoption of results by management will result in an opportunity for operators to improve planning and profitability of their fishing operations through understanding of the future harvests that can be expected and maintenance of higher catch rates than would otherwise occur. Through these results the fishery will gain from improved recognition of sustainability for domestic and overseas marketing.

9 Further development

The construction of a spatially explicit framework such as this which aims to incorporate spatio-temporal variability using a statistically rigorous state-space approach is challenging, and there are many avenues for further development. Some important areas are:

- Increase the spatial stratification so that there are a larger number of non-closure cells at the 5 nm scale.
- Exploit the hierarchical structure of resolution of the observations (grids at 30nm from Cfish; survey and VMS available at finer scales).
- Consider the benefits of spatio-temporal random effects (actually this has already been investigated and the results were promising; however it was not able to be included in this report due to time constraints).
- Consider a finite mixture distribution over space, with each hot spot corresponding to a mixture component.
- Relax the constraint of a fixed knowledge parameter: consider gradual increases through time and perhaps even during the season.
- Incorporate the knowledge parameter concept in the catch rate standardisation.
- Incorporate the VMS processing (Trackmapper algorithm) into the modelling.
- Economics: the creation of a distribution of effort over space opens an interesting avenue for modelling the economics associated with travel distance due to fuel usage.
- Multi-species: The interaction of the Saucer Scallop and Eastern King Prawn fisheries may be more easily disentangled using this spatio-temporal framework.

The data, model framework and code are stored under DEEDI secure network directories for stock assessment. Network backup copies are run daily. Maintenance of these files will be according to the DEEDI schedule for stock assessment and future data/code/report collaborations on research projects. For future research use, access must be granted by DEEDI Fisheries Resource Assessment.

10 Planned outcomes

The project outputs provided the framework to improve the management and sustainable use of Queensland saucer scallops. The outputs will contribute to long term profitability and marketability of the fishery.

The project quantified specifications to implement effort management for saucer scallops. The project outputs provided greater certainty for fisheries managers and industry for establishing updated reference points.

The project delivered on Fisheries Queensland's management priority for saucer scallops.

The project provided support for spatial monitoring, assessment and management for saucer scallops. Further, the project provided modernised methods for dynamically setting total allowable effort (TAE).

Project results were communicated through meetings with fishery mangers and Fisheries Queensland's trawl-technical-advisory-group. The project delivered a set of management reference points to implement within the Queensland trawl plan review. This will allow the fishery to be sustainably and profitably managed which will benefit all involved in the Queensland scallop fishery. The meetings and presentations better informed stakeholders and managers about the important need to spatially monitor and manage saucer scallops. The FRDC project and results was further promoted through an open DEEDI seminar forum along side Dr Carl Walters in Brisbane June 2011.

11 Conclusion

The modelling framework initiated in FRDC Project 2006/024 was updated to estimate reference points using all available data sources and modelling spatio-temporal recruitment variability. The incorporation of historical catch and catch-rates played an important role in reducing stock-recruitment uncertainty, although two hypotheses on stock-recruitment dynamics remain – a large unproductive stock or a smaller more productive stock. These two hypotheses (in fact a continuum of hypotheses along this gradient) result in large uncertainty in E_{MSY}, however MSY was estimated with greater confidence at around 500-800 tonnes.

The updated framework was relatively detailed spatially, consisting of 43 distinct strata, allowing the assessment of various management strategies relating to the spatial closures in terms of MSY and E_{MSY}. One of the proposed spatial management strategies involves moving from the current rotational system of 15 months closed, 9 months open, to a three year schedule of 33 months closed, 3 months open. This would induce a more pulse-like fishery. While MSY and E_{MSY} indicators were largely unaffected by this strategy, the catch-rate indicator showed an improvement of 21% over the status quo based on the posterior mode.

The framework can now be used to test new management strategies with relative ease. It is also a flexible and robust foundation for future modelling work.

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13 Appendix 1: Intellectual property

The research was for the public domain. The report and any resulting manuscripts are intended for wide dissemination and promotion.

14 Appendix 2: Staff

The following table lists project staff involved in the project.

Name	Government organisation	Funding
Campbell, Alex	DEEDI, Queensland	FRDC and in-kind
Leigh, George	DEEDI, Queensland	In-kind
O'Neill, Michael	DEEDI, Queensland	In-kind
Jebreen, Eddie	DEEDI, Queensland	In-kind
Wang, You-Gan	CARM, University of Queensland	In-kind

15 Appendix 3: Data

15.1 Spatial stratification and closure schedules

The fishery was spatially stratified at the 30-minute scale by the 19 highest effort grid squares (summed over the entire CFish time span, 1988–2009) which together accounted for more than 97.65% of all effort. The finer-scale 5-minute grid squares are areas that have been closed to fishing at some point in time. The cells are numbered such that the highest effort grid has the number 1, then any closure cells within the grid are numbered bottom to top then left to right, then the next highest effort grid receives the next number and so on. Each cell has a 'fishable-area' (A_k) associated with it, calculated from the VMS data-set: A_k is the total area within cell k that has had non-zero catch at any point in time during the VMS data years (2001–2006).

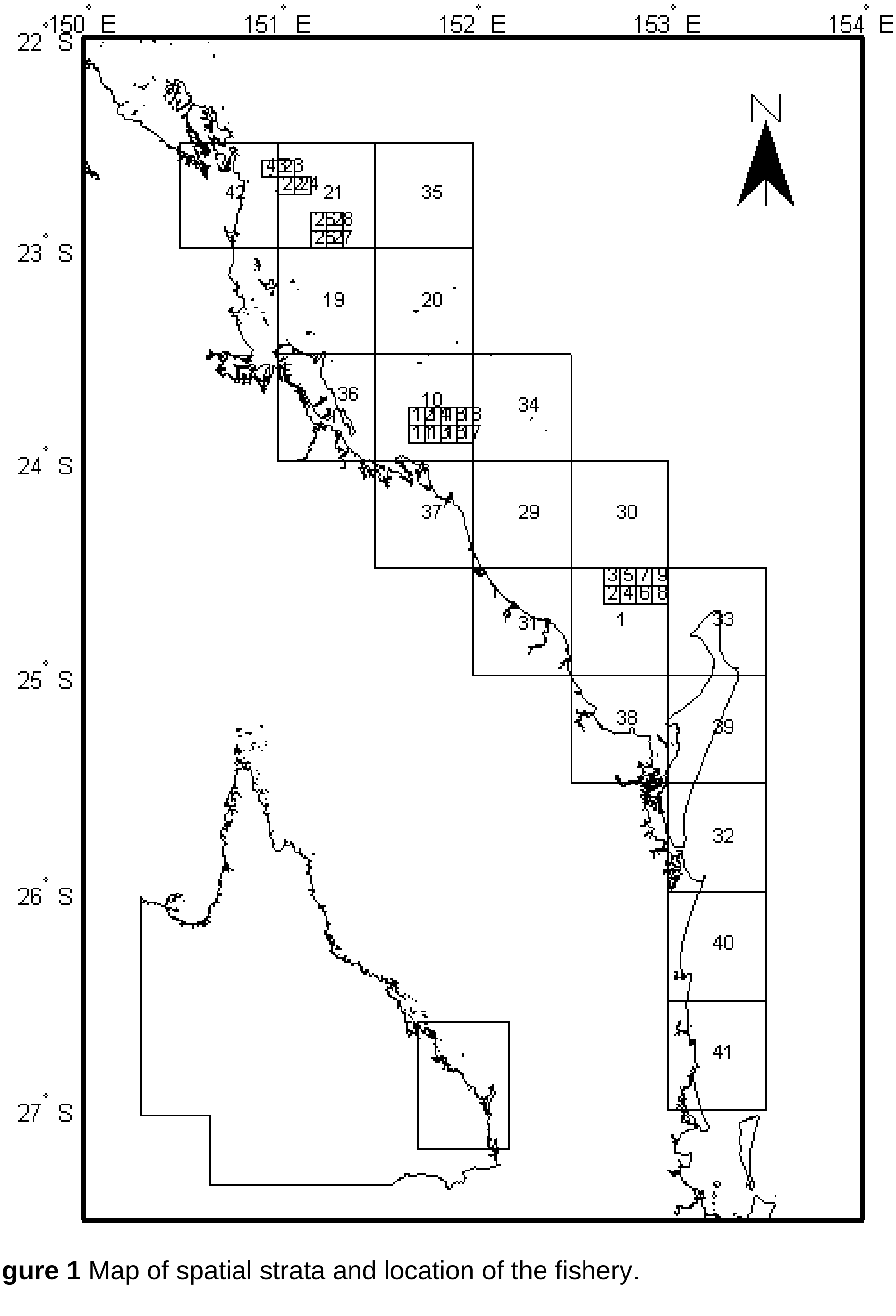

Figure 1 Map of spatial strata and location of the fishery.

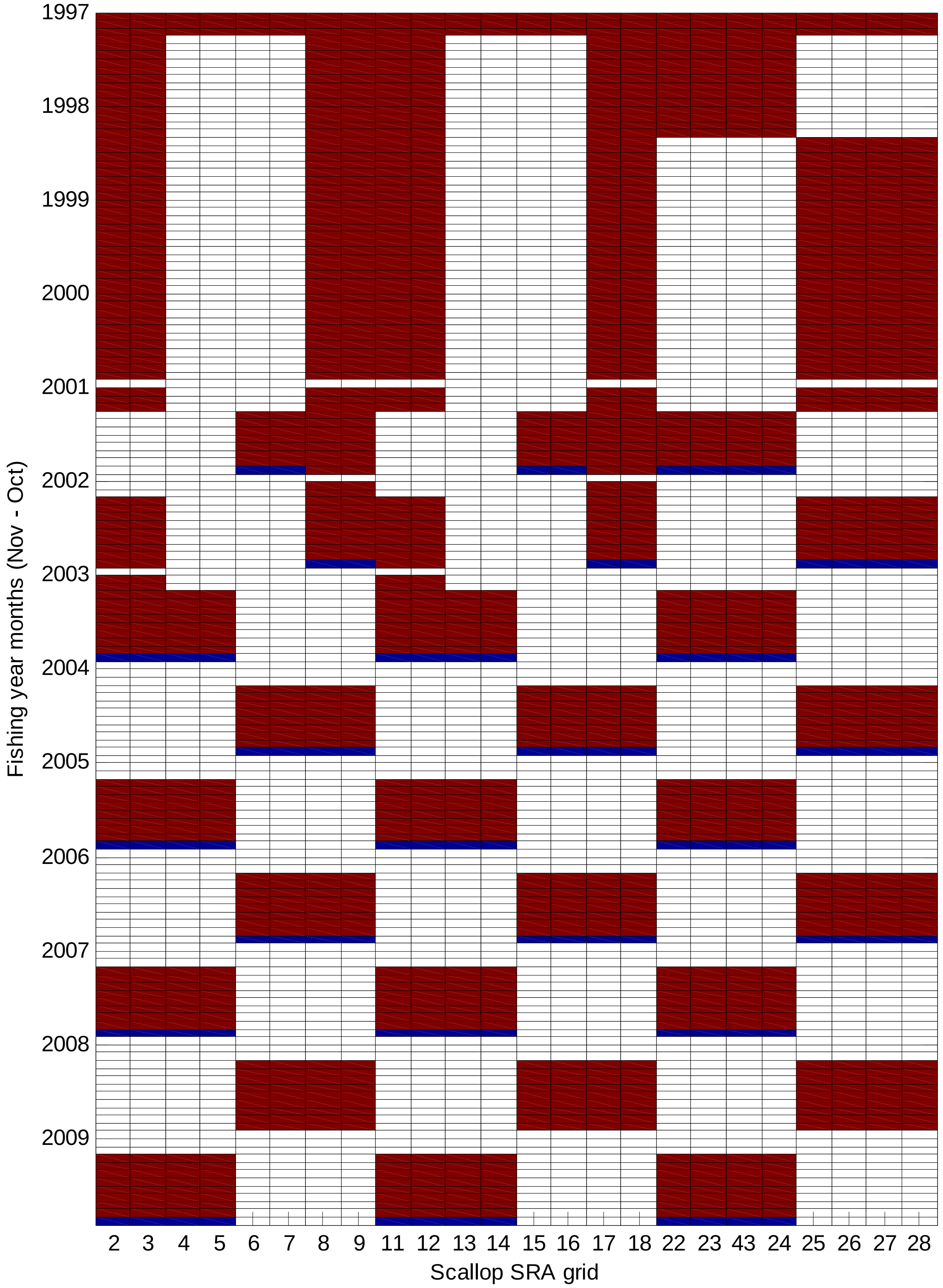

Figure 2 Historical closure schedules. Red indicates open, white indicates closed, and blue cells were closed for roughly half of the month.

15.2 Catch and effort

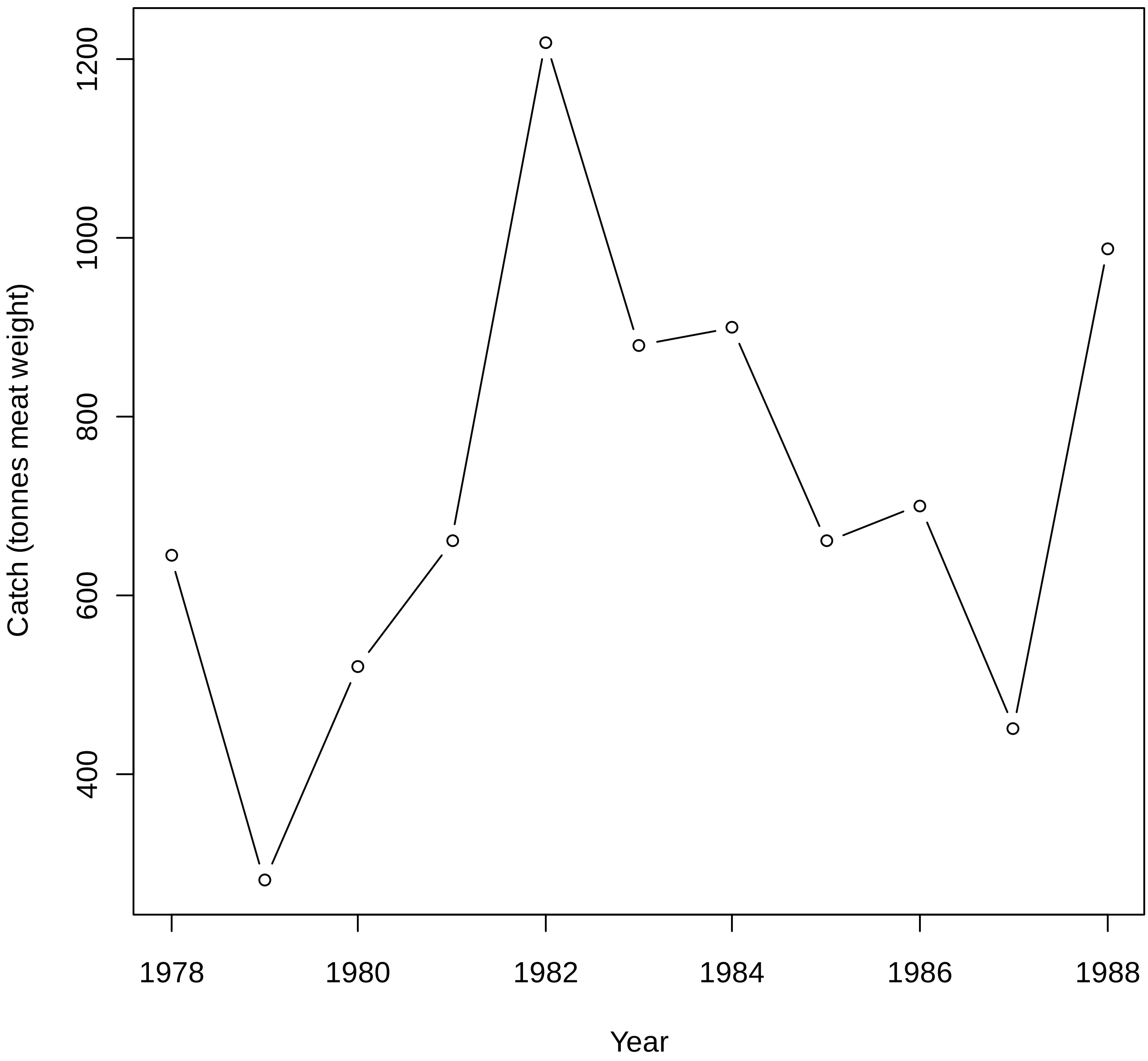

Figure 3 Total annual catch between 1978 and 1988 from (Dredge 2006).

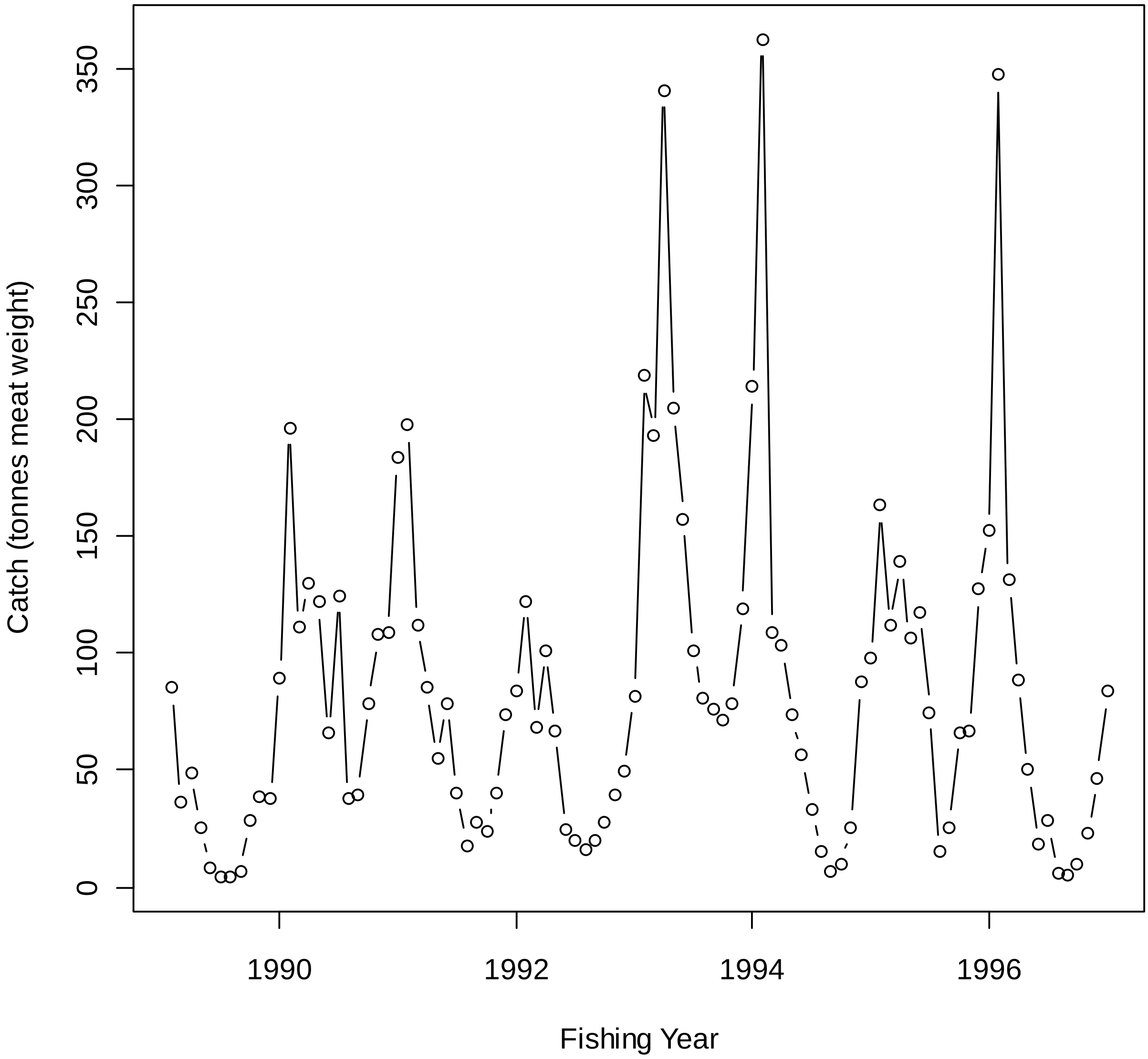

Figure 4 Monthly catch between November 1988 and October 1996 from Cfish.

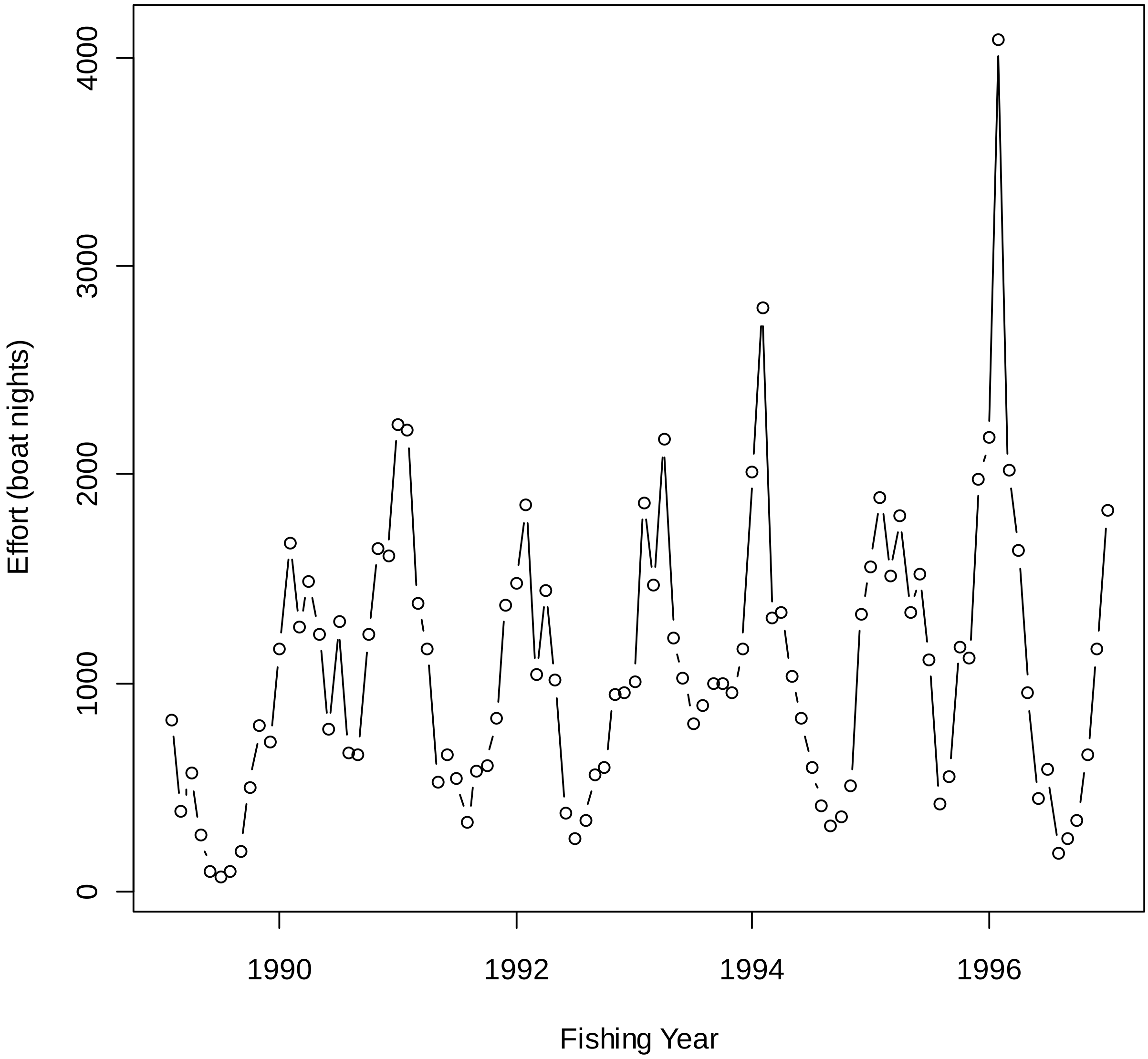

Figure 5 Monthly effort between November 1988 and October 1996 from Cfish.

Table 12 Cfish derived monthly catch estimates, in kg of meat weight, for each of the top 19 effort grids, from November 1996 to October 2009.

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Nov-96	9708	19789	19865	4704	24866	22391	3298	3785	1608	13	3096	6148	1412	1992	318	156	5976	1470	0
Dec-96	7136	7210	8900	4781	8660	9214	3459	1439	298	177	2063	6315	1483	520	111	606	3742	1272	36
Jan-97	3494	5084	4193	3691	3971	9377	1046	1145	1839	714	763	1818	922	4151	0	1396	367	169	233
Feb-97	3919	7115	4662	2783	10474	17355	1290	4329	2211	439	1151	4602	894	1566	53	451	1100	274	136
Mar-97	1356	4905	1484	3426	2601	8158	948	1016	4426	127	37	1798	589	140	36	1319	1784	72	0
Apr-97	1175	2511	2138	2817	5240	10262	1196	1548	2248	334	1407	3135	1067	1358	0	2106	1009	351	0
May-97	248	873	1363	286	617	914	149	638	157	26	623	278	158	0	23	91	107	10	28
Jun-97	153	1595	497	271	1069	545	0	275	150	41	439	100	345	45	0	80	26	395	0
Jul-97	745	2598	1076	787	174	6083	398	1242	32	76	962	2685	436	440	11	16	369	0	0
Aug-97	5604	4501	4429	1733	3744	17732	1018	2272	1796	36	1384	7510	1102	850	109	196	2471	0	5
Sep-97	10099	9990	4302	2039	2801	13384	1229	1977	4566	327	2200	5068	375	740	3	666	3402	0	37
Oct-97	15730	9155	7102	4692	11936	19466	2124	3326	1877	814	3598	6626	1269	1025	907	11788	3739	74	0
Nov-97	16474	14641	18007	10643	37506	34941	6796	2643	4380	1396	6367	22104	4506	6654	806	57827	6495	25	1316
Dec-97	12770	14421	11972	7058	15849	17042	2702	1243	730	469	3032	8590	3795	5697	338	7379	1934	2513	435
Jan-98	12266	11738	12197	4117	15711	7247	4297	2296	297	1753	2167	2015	2705	4295	743	1956	114	303	1820
Feb-98	9413	8270	16555	4679	28148	5850	2125	2452	343	1500	1176	2161	4095	2333	914	1897	267	64	2103
Mar-98	11546	10439	5559	4093	5770	3717	677	4091	391	994	74	298	2697	334	171	388	85	15	6946
Apr-98	14649	5679	5837	6112	3548	3720	736	1901	610	412	635	399	680	0	998	1485	175	0	1026
May-98	5412	883	408	969	187	867	668	308	59	44	179	30	185	0	114	12	54	9	35
Jun-98	6112	1098	577	1324	96	1591	495	1109	0	115	58	98	302	3	239	40	0	1	0
Jul-98	8120	1695	2951	757	24	3349	2051	1892	0	1275	0	415	209	13	367	112	20	0	286
Aug-98	10164	1488	1269	963	29	6442	1877	2504	633	4078	271	186	56	36	306	123	0	0	0
Sep-98	16868	5455	1508	340	505	2748	2121	1897	5870	7108	285	35	11	61	403	374	526	3	3
Oct-98	25739	8608	4496	2065	3549	5136	3611	3746	6722	7327	368	1163	187	0	4617	72	3427	17	314
Nov-98	23335	31992	25403	15676	28744	50878	6146	10110	10096	8472	5268	6810	7232	1894	5978	756	8556	247	261
Dec-	12778	5074	25267	8030	5872	29680	1952	5710	2014	4159	3526	14	1416	4699	477	136	0	23	176

98																			
Jan-99	11631	9217	28370	8610	9227	17294	2379	6723	28	2837	1855	1265	3753	3032	348	0	0	0	1216
Feb-99	14466	11354	20293	8684	10774	8821	2366	2727	53	1625	2419	926	3661	1195	338	0	0	0	382
Mar-99	4255	7880	6842	4290	5968	8804	785	1724	135	1187	807	0	1116	218	35	23	9	0	0
Apr-99	2746	5323	1079	1241	222	2658	204	384	3	1812	248	232	65	0	26	67	3	0	0
May-99	819	1120	423	386	78	946	0	1140	0	345	416	1	0	0	6	6	0	0	6
Jun-99	881	1352	395	344	275	225	0	840	330	280	33	0	120	0	5	0	0	0	0
Jul-99	1930	1704	1339	572	305	464	5	305	0	763	310	158	245	0	173	36	0	0	0
Aug-99	6805	3003	3741	2375	762	906	1664	978	37	1565	267	210	1088	369	316	333	0	0	8
Sep-99	7726	7816	5204	3032	1054	4188	3241	1202	1	835	1869	207	3495	663	770	8	0	0	0
Oct-99	15236	20566	10496	5692	17025	20344	3755	1412	0	1415	1728	158	6281	2423	357	6	0	17	0
Nov-99	25375	28764	21876	16920	41342	33428	3047	2247	0	3734	3235	5489	8094	3525	487	20	0	13	181
Dec-99	23938	17803	10594	7130	10460	16276	2652	1797	35	3422	3184	1018	3276	1570	1623	21	0	9	80
Jan-00	29587	18811	11942	6437	7469	17140	2470	991	0	12437	2836	530	4995	2356	117	330	0	0	339
Feb-00	14397	5514	3372	3627	4864	1607	1161	1757	38	47330	54	415	865	450	1437	834	0	0	0
Mar-00	15026	11095	7413	5470	3987	12259	1955	1197	2619	19928	759	106	3957	2518	2478	844	0	0	18
Apr-00	5393	5486	4756	3188	1647	3869	629	923	5497	12687	1009	426	1948	1955	737	862	0	0	26
May-00	3075	938	1395	239	0	575	82	26	406	4076	177	6	66	85	400	221	543	3	73
Jun-00	625	104	964	59	11	336	213	295	2365	817	41	0	11	142	278	627	656	0	0
Jul-00	1592	3167	1057	386	9	650	613	25	3959	3253	112	64	794	243	549	182	248	0	21
Aug-00	3057	5478	2562	629	448	2120	2249	533	2422	3778	395	142	1522	5703	1494	2465	5639	1003	226
Sep-00	6821	5662	2000	837	1759	3531	2629	447	7485	3500	2124	213	1830	746	736	545	19529	21295	1764
Oct-00	318	0	0	0	0	231	660	0	0	186	93	0	216	0	228	738	0	0	0
Nov-00	19548	21572	9810	4265	42077	8154	4441	1660	38657	10469	3724	6127	5169	4939	2477	52808	21030	1758	328
Dec-00	11596	9349	8272	2091	9076	9005	4134	1180	8551	3804	5950	2530	6358	2250	996	11168	1805	274	0
Jan-01	19701	19188	15133	7367	60419	11307	1762	480	4630	9164	9362	13566	8207	2803	1077	17076	8520	476	0
Feb-01	27490	92614	2984	2368	42841	9107	840	1378	637	3940	2820	0	1726	3474	487	371	8024	36267	213
Mar-01	4396	7330	7787	3916	23398	17232	1686	1229	222	1760	1449	1654	611	4050	111	500	1561	700	1075

Apr-01	3023	4971	4332	1637	13989	4156	1226	237	369	959	429	3001	423	2671	128	374	61	0	5
May-01	1200	2990	500	1453	4276	2150	238	530	307	493	656	548	30	415	84	95	0	0	0
Jun-01	1551	3454	756	299	673	2322	640	62	34	105	45	341	206	329	565	5	5	488	97
Jul-01	2046	7873	2650	1305	4796	1424	523	405	1	38	510	1185	190	1656	280	35	5	1519	303
Aug-01	4703	2300	3310	2896	6592	5863	678	636	8	508	1025	4044	116	650	410	13	13	59	317
Sep-01	3628	3094	2930	1802	8912	2293	340	169	63	677	2043	1012	161	346	453	191	2087	116	767
Oct-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-01	15872	22441	18475	10206	64716	15041	4103	2630	1380	2624	4073	18376	3154	4901	5062	255	1814	378	25686
Dec-01	7020	6414	4674	3029	6376	4413	1062	294	557	1048	747	5662	1585	903	1277	82	620	58	2118
Jan-02	10831	11740	10216	1290	140258	1223	510	813	37	276	1672	40183	392	663	392	80	577	43	22150
Feb-02	4893	9468	3221	1189	24702	1663	212	144	49	4122	4287	10112	545	186	0	135	8	54	2954
Mar-02	10294	730	132	388	1144	500	2	508	0	1925	1847	117	329	1524	0	1076	0	33	619
Apr-02	9340	918	398	167	1339	2002	654	317	447	1152	864	405	0	418	59	16	0	0	496
May-02	1849	170	267	276	167	1099	209	0	21	134	880	0	49	0	211	0	0	0	0
Jun-02	1771	50	25	55	201	609	23	60	0	12	171	0	0	18	28	0	0	0	0
Jul-02	7699	175	50	90	0	2360	864	28	0	490	234	0	0	0	11	16	0	0	0
Aug-02	7246	65	28	398	28	1712	305	485	0	728	430	15	45	215	585	15	5	0	0
Sep-02	4840	707	11	307	166	1061	66	232	0	465	309	11	0	508	1663	0	17	0	0
Oct-02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-02	22815	12538	411	1763	320	12810	2633	1181	3	3923	1448	209	104	1396	3947	111	0	74	13
Dec-02	11019	5971	36	1021	111	909	946	147	0	970	919	191	479	458	2824	150	0	32	0
Jan-03	53905	50848	2566	5285	6658	775	2700	396	2534	6736	6010	637	3957	1303	2198	0	488	38	0
Feb-03	6487	6864	2278	1754	4719	280	269	0	734	1346	1333	0	226	15	1803	105	102	0	0
Mar-03	7058	470	2641	1608	3645	71	227	0	0	1481	93	235	36	826	3143	150	0	0	0
Apr-03	3560	1099	0	169	423	88	83	7	72	267	1248	0	111	1063	2035	0	0	0	0
May-03	1214	612	6	27	6	248	60	146	0	114	359	54	36	0	191	438	0	0	0
Jun-03	1029	55	25	226	3	359	131	137	130	25	298	58	0	0	26	50	0	0	0
Jul-03	785	0	46	550	55	176	0	13	390	0	99	28	0	20	195	0	0	340	0

Aug-03	3937	1271	148	933	85	13	63	63	228	540	70	128	50	1275	298	0	465	0	5
Sep-03	7247	2489	406	737	72	105	162	204	385	435	0	17	143	451	358	0	102	0	0
Oct-03	0	0	0	668	0	0	0	0	0	0	0	1750	0	0	0	0	0	0	0
Nov-03	32689	9466	2847	464	19419	2916	356	166	21822	2652	2720	1370	789	0	5401	545	4184	124	0
Dec-03	10079	6601	1528	703	3706	1003	119	0	669	523	2568	1535	464	295	1644	30	683	19	0
Jan-04	14910	41823	5975	2466	39115	615	265	717	11363	98	7136	1586	1671	742	5187	0	1108	21	0
Feb-04	11252	9131	1019	3307	1000	496	444	0	6823	105	1683	4	1391	0	4031	0	3978	25	15
Mar-04	10411	4627	186	577	91	65	179	1861	7	158	1254	35	1161	0	4566	0	7	0	345
Apr-04	24274	3443	649	139	20	26	442	2597	360	146	970	0	996	0	7519	288	139	0	0
May-04	2890	275	271	103	164	74	191	23	571	199	183	78	115	0	247	555	10	0	0
Jun-04	6390	1038	452	328	0	3	151	287	444	10	626	0	39	419	1624	164	0	0	26
Jul-04	8743	2208	62	824	0	578	461	1463	16	14	417	0	0	0	2721	0	0	0	5
Aug-04	9735	17014	173	582	32	3602	885	1250	19	0	663	162	229	149	1883	0	5	0	11
Sep-04	8834	1646	345	185	6	3178	1526	745	83	26	1755	0	46	0	312	0	143	0	0
Oct-04	36	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0
Nov-04	46563	20040	3900	8520	11652	7110	3557	2203	10613	326	13624	293	806	237	19410	1730	5874	35	460
Dec-04	16360	11239	1898	6888	2407	2736	3541	2063	559	283	4919	140	337	0	4878	1580	698	116	36
Jan-05	138245	164000	4159	5590	2697	4184	5096	4078	479	3754	7444	1072	663	5412	1485	261	0	0	0
Feb-05	14568	8837	1728	4176	266	1074	3380	2195	5012	31	2504	331	55	102	16	128	66	8	0
Mar-05	11069	4787	1955	4073	340	316	1172	163	3075	19	489	0	0	191	425	7	9	43	0
Apr-05	9998	2513	615	2239	0	651	822	1154	239	7	625	0	7	0	644	7172	324	31	0
May-05	4798	2008	844	832	27	772	791	326	281	0	716	60	139	344	436	6	0	6	0
Jun-05	2188	687	546	540	10	112	346	76	17	5	508	0	335	0	46	0	0	0	0
Jul-05	3953	150	665	899	0	550	926	238	8	0	160	53	15	8	65	501	0	0	0
Aug-05	3201	222	1181	738	86	456	1208	162	1387	0	117	171	60	0	0	103	0	0	0
Sep-05	5780	1128	484	869	897	1078	1480	98	292	6	685	347	0	0	66	435	0	0	0
Oct-05	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-05	22166	8168	1408	8070	51133	1188	1817	2343	16843	280	1401	26508	113	146	1032	506	4258	1301	0

Dec-05	2516	4423	2612	6494	7710	518	2068	121	4859	14	1624	2663	156	85	598	142	518	63	0
Jan-06	9664	16341	4202	8592	29669	239	2793	142	7363	25	4491	3286	641	72	248	0	557	0	0
Feb-06	1744	1184	2171	2147	3614	40	845	0	2692	23	1395	449	489	16	22	0	323	0	0
Mar-06	1524	550	1177	1408	1779	37	741	29	22	22	392	59	0	44	18	0	0	0	149
Apr-06	2668	1814	904	1438	124	247	2236	20	3751	33	244	0	26	637	96	0	0	0	0
May-06	1011	36	18	829	0	233	415	6	4407	3	166	0	36	0	203	6	0	6	0
Jun-06	1063	0	140	280	0	571	270	0	1230	10	737	0	0	0	87	0	0	0	0
Jul-06	882	92	370	452	0	1845	307	17	6489	0	246	0	6	0	108	0	132	262	0
Aug-06	1113	75	1263	345	25	2737	1616	350	4651	0	139	25	10	0	145	0	478	0	0
Sep-06	2000	260	1985	97	470	2722	1072	130	3546	0	170	6	0	1095	61	11	0	0	0
Oct-06	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-06	10607	9775	23547	10554	16037	4225	3982	1312	113392	5636	1646	346	7	0	208	2524	8589	975	0
Dec-06	1279	2344	2231	13757	2175	3000	1067	505	9434	653	1774	284	0	0	0	751	1756	318	0
Jan-07	155713	26101	12876	14087	93781	1511	13402	494	9229	2450	1456	3859	28	417	106	71	106	1619	0
Feb-07	6073	1255	7958	8454	12537	665	516	0	1385	0	815	2343	68	0	0	0	1486	42	0
Mar-07	8099	4795	2399	2650	8032	731	218	362	628	0	557	1166	317	0	30	15	1440	13	0
Apr-07	6129	3863	5905	2664	6370	958	830	13	7148	801	909	189	606	0	0	368	432	17	0
May-07	1424	2600	1686	1466	139	4799	998	18	382	712	869	0	284	259	54	0	2274	0	103
Jun-07	122	13748	206	1351	0	3217	36	16	2264	0	845	30	91	342	340	15	428	0	45
Jul-07	1063	11570	2510	2148	267	886	81	68	7313	0	330	640	267	242	15	181	635	0	10
Aug-07	2536	4831	6241	3872	592	179	15	10	9658	386	263	424	0	167	5	934	0	56	0
Sep-07	12152	963	2058	2952	671	328	4886	3	1820	612	3	629	634	45	0	17	351	0	0
Oct-07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-07	31236	10013	13749	9212	22421	654	1989	72	47295	2211	1093	4511	4599	746	170	1420	32149	556	448
Dec-07	6882	3867	11075	4705	14969	3556	3130	101	28932	123	2375	5120	855	1637	201	7	8415	507	416
Jan-08	10289	63536	9269	7144	40643	369	43	85	15231	128	993	5577	4927	106	128	306	16286	142	0
Feb-08	7949	7184	2374	6889	25445	174	250	8	3819	2200	444	60	605	703	280	265	1537	2	0
Mar-08	7971	1639	5271	4278	3487	339	144	7	6025	3509	1263	0	693	0	502	47	433	0	0

Apr-08	6427	2800	2879	3122	636	318	1069	13	12923	1030	144	190	944	0	161	2049	3102	157	0
May-08	2848	2073	844	894	419	363	1089	0	4117	209	316	59	369	0	216	47	3970	0	0
Jun-08	1769	475	351	1525	41	511	655	5	1473	0	586	263	315	114	0	5	516	0	0
Jul-08	2858	1039	667	1240	236	652	703	0	477	0	877	141	51	0	46	8	0	0	0
Aug-08	1465	1452	1900	1207	0	290	540	0	102	209	153	191	0	112	196	0	46	0	0
Sep-08	3586	1210	2218	1421	0	342	1741	0	45	817	93	0	67	0	246	17	39	0	0
Oct-08	268	1496	686	0	0	0	368	0	0	0	405	0	1022	910	0	0	156	0	0
Nov-08	38684	11107	12190	12442	26851	3996	5607	47	8334	3092	4394	10443	10914	286	0	236	2265	825	33
Dec-08	12215	6223	6977	10167	12424	2183	439	397	4493	524	5298	5344	4096	893	0	870	716	906	0
Jan-09	135469	23313	3508	10197	15019	188	3104	2852	6275	5888	407	2664	1764	25	0	8960	0	30	227
Feb-09	18958	6066	6751	7516	9680	390	2250	773	5248	10389	1185	1605	1073	0	0	8	11	0	263
Mar-09	18050	1622	3198	2935	2835	374	0	0	8255	2691	137	209	2928	0	94	7	43	0	374
Apr-09	17838	426	913	676	549	445	1554	884	1820	1827	3601	13	1066	0	7	0	15	0	0
May-09	8387	915	2622	277	19	1237	1444	402	83	344	818	0	108	0	33	77	0	0	0
Jun-09	4932	2375	594	541	160	826	1109	33	2149	8	1019	0	0	0	55	0	0	5	0
Jul-09	5708	7104	2508	555	0	360	882	5	504	182	1312	0	9465	0	0	5	707	0	0
Aug-09	13015	7299	1547	303	177	2962	2249	0	222	334	2497	131	13551	0	238	354	57	0	0
Sep-09	9383	7673	6309	61	297	850	1249	0	1700	8	2508	94	1546	611	176	0	17	0	0
Oct-09	0	0	0	0	0	102	0	0	0	0	1779	0	642	0	0	0	0	0	0

Table 13 Cfish derived monthly effort estimates, in boat nights, for each of the top 19 effort grids, from November 1996 to October 2009

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Nov-96	277	453	422	156	393	448	78	92	32	2	71	120	47	39	10	4	90	43	0
Dec-96	271	207	241	171	216	245	75	54	15	25	54	169	46	13	5	13	66	37	2
Jan-97	124	151	134	124	93	208	27	37	63	46	24	76	26	76	0	35	9	23	9
Feb-97	131	190	132	92	120	342	39	95	100	33	18	85	26	29	2	32	41	20	1
Mar-97	50	117	57	88	46	184	30	28	165	8	4	36	13	4	2	62	39	9	0
Apr-97	38	79	73	78	85	235	32	45	96	17	38	61	37	33	0	79	36	25	0
May-97	41	53	56	29	39	41	14	50	15	5	41	17	12	0	2	15	12	1	2

Jun-97	18	62	35	31	42	31	0	20	15	7	16	12	16	2	0	13	5	10	0
Jul-97	32	64	47	68	7	150	16	46	4	7	23	80	22	11	4	2	10	0	0
Aug-97	222	169	164	97	95	470	51	67	25	2	46	194	44	22	7	4	48	0	1
Sep-97	410	295	151	87	71	378	46	72	94	30	62	146	17	18	1	26	89	0	5
Oct-97	560	239	180	155	192	432	53	100	51	57	68	124	32	25	41	182	77	11	0
Nov-97	375	245	299	198	464	564	116	82	74	39	88	253	84	106	40	454	79	6	20
Dec-97	364	245	218	167	227	330	55	61	23	29	50	147	73	86	34	125	29	35	11
Jan-98	317	166	185	91	203	130	61	41	32	49	28	56	49	59	57	80	5	31	26
Feb-98	235	124	264	86	297	96	34	57	25	32	21	52	61	31	34	39	7	14	18
Mar-98	212	167	116	112	64	61	10	66	21	27	2	12	50	4	24	28	8	5	38
Apr-98	258	68	114	135	42	54	15	45	42	12	9	7	21	0	20	61	12	0	12
May-98	142	32	20	58	14	22	20	11	9	6	10	2	13	0	28	2	7	4	3
Jun-98	191	46	26	96	14	39	15	35	0	11	8	17	23	1	9	4	0	1	0
Jul-98	222	57	96	107	2	54	33	43	0	53	0	27	12	2	16	3	1	0	7
Aug-98	258	39	42	68	2	114	42	55	7	136	9	16	2	1	7	6	0	0	0
Sep-98	395	75	35	15	10	54	46	50	47	215	7	3	1	1	13	8	6	1	1
Oct-98	494	100	71	41	29	78	44	77	47	199	4	30	8	0	87	2	21	6	6
Nov-98	400	263	224	166	173	350	50	87	73	179	33	46	68	22	98	13	55	5	2
Dec-98	248	49	255	127	54	255	26	71	23	113	23	3	14	44	13	4	0	6	4
Jan-99	240	77	302	140	58	197	35	93	4	80	17	10	23	31	17	0	0	0	17
Feb-99	261	104	213	119	78	106	27	67	2	37	19	11	37	16	9	0	0	0	7
Mar-99	112	99	97	94	46	102	17	41	4	36	9	0	13	3	1	4	2	0	0
Apr-99	82	84	25	31	4	49	7	12	1	60	7	4	2	0	1	9	1	0	0
May-99	41	38	20	38	4	26	0	20	0	30	11	1	0	0	1	1	0	0	1
Jun-99	24	42	18	31	12	10	0	23	5	33	2	0	5	0	1	0	0	0	0
Jul-99	90	67	42	33	15	19	1	7	0	59	16	14	8	0	13	4	0	0	0
Aug-99	261	68	105	95	25	31	36	46	4	103	11	13	28	10	19	14	0	0	1
Sep-99	270	153	131	81	33	96	65	42	1	50	30	13	61	15	39	1	0	0	0
Oct-99	445	332	168	117	202	337	73	40	0	77	32	14	101	48	16	1	0	7	0
Nov-99	506	401	307	226	383	413	47	48	0	101	46	56	116	48	18	1	0	7	6
Dec-99	560	281	190	141	166	202	45	37	1	123	47	16	59	28	42	1	0	3	7
Jan-00	599	273	195	127	126	226	52	15	0	175	44	11	84	38	6	9	0	0	10
Feb-00	324	102	63	78	59	39	20	32	1	538	1	6	15	5	48	26	0	0	0
Mar-00	388	188	149	115	76	223	51	36	34	376	19	2	64	35	80	31	0	0	2
Apr-00	160	144	106	105	32	98	19	35	79	230	25	8	39	33	29	15	0	0	1
May-00	148	36	56	39	0	43	11	3	30	145	11	1	5	5	14	20	4	1	4

Jun-00	50	4	47	10	1	23	18	13	73	38	8	0	1	10	18	26	12	0	0
Jul-00	76	76	56	40	2	44	42	4	119	122	16	13	18	5	25	21	9	0	4
Aug-00	117	117	49	46	23	51	62	14	61	145	11	27	35	108	46	38	50	7	1
Sep-00	256	130	39	31	36	100	77	12	113	128	55	17	34	27	27	12	182	191	21
Oct-00	9	0	0	0	0	8	13	0	0	2	3	0	3	0	3	8	0	0	0
Nov-00	428	240	109	55	320	139	82	25	386	224	47	43	70	66	57	351	170	27	2
Dec-00	262	128	125	31	110	146	56	17	155	102	81	49	84	41	30	154	21	9	0
Jan-01	320	199	165	87	439	162	44	10	112	183	98	101	65	40	22	194	69	27	0
Feb-01	251	379	29	32	171	103	23	10	43	77	17	0	16	36	9	34	22	92	3
Mar-01	122	96	111	63	185	237	25	27	23	49	27	15	12	57	6	41	18	5	13
Apr-01	63	73	58	27	110	85	22	7	51	40	19	32	16	51	3	29	3	0	2
May-01	43	50	20	46	85	73	18	12	43	29	27	19	2	30	3	15	0	0	0
Jun-01	67	48	23	13	16	54	17	7	9	10	4	14	5	7	23	1	1	4	4
Jul-01	71	160	48	52	76	60	15	15	1	4	18	26	4	55	13	4	1	28	6
Aug-01	150	59	70	82	74	145	25	13	5	28	34	56	6	22	15	4	2	2	9
Sep-01	131	69	65	39	100	70	18	8	2	29	42	20	4	12	11	10	9	3	13
Oct-01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-01	319	278	266	158	544	226	56	49	29	63	56	155	40	73	90	16	20	12	249
Dec-01	144	103	70	58	86	103	23	8	11	34	13	63	22	21	26	10	9	2	48
Jan-02	115	85	54	20	586	23	14	6	5	8	16	167	6	4	6	5	11	2	116
Feb-02	83	91	40	22	223	27	9	1	7	75	45	64	10	3	0	18	1	11	36
Mar-02	118	13	3	8	16	13	2	18	0	43	28	6	13	19	0	14	0	5	16
Apr-02	112	15	13	4	14	32	5	6	6	32	38	10	0	7	2	2	0	0	8
May-02	69	4	6	9	4	29	22	0	4	3	46	0	1	0	7	0	0	0	0
Jun-02	50	4	2	7	2	27	5	5	0	1	24	0	0	1	1	0	0	0	0
Jul-02	116	6	3	15	0	49	12	8	0	21	9	0	0	0	2	2	0	0	0
Aug-02	139	3	5	33	4	41	9	10	0	18	20	4	2	4	11	1	1	0	0
Sep-02	104	15	1	31	11	23	2	10	0	21	15	5	0	12	35	0	1	0	0
Oct-02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-02	300	146	27	55	26	175	51	14	1	86	28	27	2	15	58	2	0	10	1
Dec-02	194	70	5	30	7	18	25	3	0	30	12	18	7	6	46	4	0	6	0
Jan-03	518	351	30	89	50	18	48	6	18	109	82	14	43	11	35	0	3	6	0
Feb-03	103	86	31	39	47	10	19	0	9	24	28	0	3	1	21	1	2	0	0
Mar-03	126	7	33	39	39	2	23	0	0	27	12	3	1	8	47	3	0	0	0
Apr-03	80	16	0	7	8	3	11	1	3	9	16	0	2	12	32	0	0	0	0
May-03	48	6	1	7	1	17	17	8	0	4	7	9	2	0	8	5	0	0	0

Jun-03	54	7	2	32	1	21	9	11	3	1	15	12	0	0	3	2	0	0	0
Jul-03	55	0	4	57	3	12	0	2	6	0	14	6	0	1	11	0	0	6	0
Aug-03	135	31	9	51	7	2	10	9	2	18	8	12	1	18	13	0	10	0	1
Sep-03	146	42	14	26	1	4	14	6	8	16	0	3	3	6	10	0	3	0	0
Oct-03	0	0	0	10	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0
Nov-03	381	102	31	32	125	37	23	4	149	47	37	7	8	0	72	6	19	12	0
Dec-03	182	83	19	30	36	16	13	0	13	17	29	18	5	5	33	1	8	3	0
Jan-04	205	409	50	58	248	17	22	6	80	2	101	32	20	8	77	0	9	3	0
Feb-04	157	103	17	70	20	13	21	0	63	2	29	2	20	0	52	0	37	7	1
Mar-04	113	53	6	14	3	3	13	19	1	3	21	1	18	0	51	0	1	0	1
Apr-04	241	40	14	6	1	1	19	26	18	2	16	0	19	0	79	12	4	0	0
May-04	63	8	13	4	5	12	12	4	28	9	31	4	2	0	12	8	2	0	0
Jun-04	139	17	7	22	0	1	15	9	57	1	31	0	1	6	33	1	0	0	1
Jul-04	194	24	6	55	0	15	22	28	6	2	18	0	0	0	35	0	0	0	1
Aug-04	237	139	18	43	3	65	20	32	6	0	20	7	2	1	29	0	1	0	2
Sep-04	206	33	17	20	1	66	30	23	2	1	48	0	2	0	10	0	3	0	0
Oct-04	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Nov-04	529	167	42	112	82	96	50	31	95	8	136	13	8	4	211	33	49	2	10
Dec-04	256	112	24	85	16	40	49	35	12	7	64	7	5	0	63	65	8	2	3
Jan-05	563	434	62	65	29	22	49	21	22	13	47	7	8	15	12	28	0	0	0
Feb-05	159	90	34	86	4	14	50	30	43	1	39	7	3	1	1	11	5	1	0
Mar-05	143	64	38	78	7	9	26	3	39	2	14	0	0	2	10	1	1	6	0
Apr-05	133	35	17	64	0	13	20	15	18	1	13	0	1	0	12	6	5	8	0
May-05	122	29	21	40	3	14	39	12	32	0	26	2	5	4	11	1	0	2	0
Jun-05	94	21	36	53	1	8	28	4	5	1	30	0	9	0	1	0	0	0	0
Jul-05	139	10	25	77	0	28	36	17	3	0	11	9	1	2	3	2	0	0	0
Aug-05	135	7	36	58	4	25	48	17	21	0	11	8	2	0	0	2	0	0	0
Sep-05	158	27	15	72	19	37	32	7	11	1	20	14	0	0	1	9	0	0	0
Oct-05	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-05	326	97	16	110	288	26	33	26	137	6	22	147	3	3	16	3	36	23	0
Dec-05	72	64	44	101	74	24	71	8	44	2	40	40	3	2	10	1	4	10	0
Jan-06	218	215	67	153	232	16	93	12	104	2	97	42	12	2	8	0	5	0	0
Feb-06	66	21	43	52	45	3	25	0	43	2	36	18	5	1	3	0	3	0	0
Mar-06	49	11	31	44	22	2	23	1	2	1	17	1	0	1	6	0	0	0	2
Apr-06	88	40	20	64	2	14	41	3	25	3	17	0	2	6	5	0	0	0	0
May-06	64	5	2	32	0	8	22	1	61	1	12	0	5	0	11	1	0	1	0

Jun-06	58	0	12	22	0	15	17	0	30	1	25	0	0	0	12	0	0	0	0
Jul-06	44	6	16	45	0	43	24	1	83	0	33	0	2	0	9	0	3	5	0
Aug-06	42	9	27	46	3	60	61	8	58	0	23	3	4	0	7	0	13	0	0
Sep-06	33	6	23	15	2	51	19	4	29	0	16	2	0	7	1	1	0	0	0
Oct-06	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-06	130	77	121	90	65	54	71	15	403	34	37	2	1	0	3	8	47	84	0
Dec-06	31	24	16	98	9	51	18	6	69	5	41	5	0	0	0	9	14	29	0
Jan-07	556	139	68	116	264	32	84	11	48	7	42	17	1	3	1	2	1	18	0
Feb-07	88	22	46	68	63	19	16	0	16	0	21	11	1	0	0	0	10	3	0
Mar-07	105	55	18	28	44	24	8	7	6	0	22	9	3	0	1	1	10	5	0
Apr-07	100	29	73	41	42	14	21	2	61	9	26	2	11	0	0	5	13	4	0
May-07	27	31	32	38	3	48	19	1	11	9	27	0	7	2	2	0	24	0	9
Jun-07	11	109	8	66	0	53	7	4	26	0	32	2	3	4	11	1	5	0	3
Jul-07	40	117	55	58	6	26	9	13	80	0	15	7	10	3	1	7	10	0	2
Aug-07	44	60	72	56	16	17	3	2	66	4	14	13	0	2	1	7	0	3	0
Sep-07	122	12	46	41	8	15	32	1	15	5	1	12	8	2	0	1	2	0	0
Oct-07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nov-07	296	67	85	69	91	7	39	2	151	30	31	16	29	4	3	6	80	21	7
Dec-07	107	41	80	38	51	42	27	3	99	6	47	24	9	14	6	1	25	25	7
Jan-08	107	313	67	61	157	10	5	4	76	4	28	23	33	1	3	20	72	5	0
Feb-08	101	91	21	56	98	10	10	1	25	24	25	1	6	8	6	35	14	1	0
Mar-08	80	30	60	50	23	8	1	4	31	25	29	0	9	0	13	6	8	0	0
Apr-08	74	57	75	43	6	10	14	1	95	16	8	3	7	0	4	16	10	1	0
May-08	56	64	22	33	8	13	14	0	45	10	17	2	10	0	9	8	14	0	0
Jun-08	45	34	21	45	1	34	29	1	21	0	59	9	7	3	0	1	5	0	0
Jul-08	40	29	14	31	10	38	16	0	16	0	41	6	2	0	2	2	0	0	0
Aug-08	51	41	34	56	0	27	16	0	3	6	8	6	0	2	6	0	9	0	0
Sep-08	56	25	33	38	0	7	25	0	3	9	7	0	1	0	6	1	4	0	0
Oct-08	6	13	6	0	0	0	4	0	0	0	6	0	10	12	0	0	4	0	0
Nov-08	278	86	85	111	119	40	34	1	46	21	49	40	60	4	0	9	12	73	2
Dec-08	130	55	68	98	55	25	5	3	40	4	69	41	34	9	0	9	5	32	0
Jan-09	505	145	40	107	73	5	14	9	15	31	12	16	20	1	0	14	0	7	1
Feb-09	162	59	75	94	40	14	21	5	38	74	17	10	7	0	0	2	1	0	3
Mar-09	152	17	42	52	24	11	0	0	60	27	3	2	20	0	1	3	1	0	4
Apr-09	141	15	22	21	7	15	18	7	15	13	13	2	9	0	1	0	2	0	0
May-09	105	25	27	16	1	23	24	6	12	5	21	0	2	0	2	16	0	0	0

Jun-09	87	15	18	41	5	18	18	4	16	1	18	0	0	0	1	0	0	1	0
Jul-09	63	28	45	46	0	10	19	1	8	3	21	0	28	0	0	1	6	0	0
Aug-09	124	53	26	19	5	17	29	0	1	8	42	3	56	0	4	7	5	0	0
Sep-09	109	48	39	1	5	11	23	0	10	1	28	2	7	5	4	0	3	0	0
Oct-09	0	0	0	0	0	1	0	0	0	0	12	0	4	0	0	0	0	0	0

Table 14 Vessel monitoring system derived (using 'trackmapper') estimates of effort, in hours, for cells 1 to 41, from December 2000 to December 2006 (October is excluded due to the fishery being closed).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
Dec-00	2292	33	77	2	0	5	1	105	157	1124	67	154	0	0	0	0	171	41	1204	413	1100	4	0	0	71	71	159	91	1561	91	10	751	507	957	241	457	634	187	1046	306	34
Jan-01	2396	308	631	0	0	0	0	71	20	1904	104	113	2	0	0	10	50	119	1163	933	4480	14	0	0	260	228	301	242	1364	28	8	611	973	766	1169	443	905	145	1421	846	41
Feb-01	786	1	1	5	1	1202	242	20	7	1926	0	0	81	7	1627	887	12	30	221	364	595	699	142	447	0	0	1	0	1193	29	3	47	344	214	4	137	208	21	29	290	697
Mar-01	939	0	0	0	0	32	9	1	0	658	0	0	17	0	131	66	27	55	1201	637	1547	335	32	156	0	2	0	2	2907	2	22	14	233	324	231	139	658	20	13	55	27
Apr-01	544	2	1	2	0	17	2	6	0	492	0	0	0	0	3	0	69	31	233	189	1189	44	0	65	1	0	0	2	819	52	3	0	58	77	577	15	402	1	0	0	0
May-01	265	0	0	0	0	17	2	101	11	290	0	0	0	0	100	6	0	0	345	131	345	8	0	0	7	0	1	0	706	18	26	21	5	26	135	24	130	18	3	0	0
Jun-01	455	0	0	0	0	52	25	8	4	136	0	0	1	2	444	25	4	4	180	99	84	11	0	11	0	0	0	0	665	0	5	11	23	4	1	50	133	234	2	0	34
Jul-01	569	0	0	16	0	28	4	41	4	1351	0	0	5	0	762	29	133	22	217	77	1156	7	0	10	0	1	0	0	794	76	4	0	4	28	231	134	417	138	4	21	299
Aug-01	1665	1	0	2	0	215	7	55	5	459	0	0	0	0	123	7	62	22	403	443	1162	12	2	11	0	22	0	0	1634	27	7	1	42	202	645	65	186	161	0	7	14
Sep-01	1212	0	0	0	0	45	6	18	3	674	0	0	2	0	303	14	68	37	651	256	1266	2	1	0	2	3	5	1	765	0	10	0	28	189	280	38	149	295	0	45	25
Nov-01	4041	2	1	17	0	1	0	2	2	3574	1	1	12	2	3	1	205	214	2762	1031	6686	103	0	5	4	1	3	7	2897	18	25	123	173	574	2139	451	565	653	15	85	7
Dec-01	1505	0	0	0	0	0	0	1	0	1018	0	8	0	0	0	0	101	56	614	382	1174	5	0	0	12	3	1	0	873	25	9	13	39	235	791	138	220	218	5	82	10
Jan-02	342	383	687	4	1	0	0	1	0	268	290	276	22	7	2	0	10	0	142	212	2880	42	0	1	647	1242	771	1330	169	5	1	10	15	143	2585	58	59	40	0	17	0
Feb-02	510	33	39	0	0	0	0	1	0	1065	15	100	6	4	0	26	9	53	323	182	1840	13	0	1	198	136	59	87	110	0	5	7	722	509	1071	136	69	4	0	11	1
Mar-02	1257	1	5	0	0	0	0	14	0	191	0	0	0	0	0	0	0	0	34	9	111	2	0	0	14	1	6	0	75	0	70	12	488	288	92	31	150	6	0	0	0
Apr-02	1181	12	84	0	0	0	0	12	0	199	6	1	2	2	0	0	2	6	10	25	125	2	0	0	2	18	0	3	334	42	3	46	169	110	155	32	34	7	0	2	0
May-02	449	2	116	0	0	0	0	16	6	56	2	2	0	0	0	0	2	46	103	7	0	0	0	0	0	0	0	0	223	8	3	0	27	15	0	95	1	20	0	0	0
Jun-02	327	3	0	0	0	0	0	6	0	27	0	0	0	0	0	0	0	0	9	19	8	0	0	0	0	0	0	0	213	2	4	0	78	25	5	7	13	11	0	0	0
Jul-02	851	1	0	0	0	0	0	0	0	55	0	0	0	0	0	0	0	0	17	9	0	0	0	0	0	0	0	0	559	143	1	0	436	52	0	2	0	22	0	0	0
Aug-02	1519	4	47	0	0	11	0	8	0	78	0	13	0	0	0	0	0	0	4	11	5	2	0	0	0	1	0	1	480	0	0	0	256	3	6	0	5	40	0	0	0
Sep-02	1263	3	20	14	0	0	0	27	10	321	9	21	0	0	0	0	0	0	0	21	82	0	0	0	0	4	0	0	261	10	3	0	212	15	1	1	16	132	0	0	0
Nov-02	3679	40	303	5	5	3	0	0	0	1597	37	113	17	4	0	3	0	0	85	53	103	0	0	0	0	0	0	0	1989	78	18	1	514	221	32	4	90	264	1	0	0
Dec-02	2190	141	122	2	0	0	0	0	0	785	4	29	3	2	0	7	0	3	0	13	13	0	0	0	0	0	0	0	403	16	43	0	121	110	0	5	4	174	0	0	0
Jan-03	3529	35	56	1460	1461	11	10	0	0	1813	6	20	1273	1081	6	12	0	0	663	585	441	3	0	30	0	0	0	0	266	169	5	222	773	656	55	104	16	354	16	31	0

Feb-03	1291	40	35	53	6	0	0	0	0	790	6	132	72	154	8	0	0	0	234	105	361	0	0	82	0	0	0	0	100	0	5	89	109	252	22	32	8	63	5	10	0
Mar-03	1711	19	32	9	37	3	1	0	0	268	0	0	0	0	0	0	0	0	184	156	501	2	0	44	0	0	0	0	13	2	0	10	103	26	28	7	13	164	0	0	0
Apr-03	815	0	0	0	0	0	0	0	0	296	0	0	16	7	1	0	0	0	13	14	82	0	0	8	0	0	0	0	1	0	6	0	46	94	0	32	31	78	0	0	0
May-03	136	8	23	18	33	0	0	0	0	69	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	49	5	0	0	48	14	0	16	7	126	24	0	0
Jun-03	201	0	25	2	2	1	0	0	0	50	0	0	0	0	0	0	0	0	4	0	4	0	0	0	0	0	0	0	88	0	5	25	0	12	1	4	6	121	7	0	0
Jul-03	146	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	18	0	0	0	0	0	0	0	53	0	1	132	4	5	0	0	6	154	0	6	0
Aug-03	1173	21	19	5	57	0	0	0	0	540	1	1	5	1	3	0	0	0	13	54	16	0	0	0	0	1	0	0	4	8	0	123	32	8	5	15	23	94	12	3	0
Sep-03	1408	5	31	10	112	10	0	0	0	670	1	0	7	0	0	0	0	0	22	19	59	0	0	0	0	0	0	0	63	7	2	33	21	0	0	18	3	176	0	33	0
Nov-03	5002	0	0	0	0	0	0	0	0	1186	0	0	0	0	0	0	0	0	172	43	1522	0	0	0	0	0	0	2	483	5	12	1795	96	200	67	110	12	639	11	168	1
Dec-03	2139	0	0	0	0	0	0	0	0	847	0	0	0	0	0	0	0	0	101	7	503	0	0	0	0	0	0	0	181	3	5	121	80	249	200	95	31	335	4	74	15
Jan-04	2071	0	0	0	0	332	7	1	4	1734	0	0	8	1	1379	1013	366	606	286	121	1681	1	0	0	17	933	67	714	80	2	1	892	47	340	218	168	52	584	4	138	0
Feb-04	1527	0	0	0	0	23	0	0	0	822	0	0	0	0	75	10	15	9	284	158	104	0	0	0	6	15	9	7	145	46	6	969	28	303	10	62	0	339	1	397	0
Mar-04	1564	0	0	0	0	1	0	0	0	374	0	0	2	1	165	132	22	65	163	74	27	0	0	0	1	6	3	7	29	0	2	0	23	140	7	21	0	246	0	0	0
Apr-04	3209	0	0	9	8	103	42	1	0	298	0	0	3	0	193	33	15	16	206	15	15	0	0	0	0	7	1	1	12	53	0	21	9	32	0	22	2	559	6	30	0
May-04	354	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	0	72	33	0	0	0	0	0	0	0	0	8	4	1	5	0	0	0	6	0	8	21	0	0
Jun-04	1157	0	0	0	0	2	3	0	0	97	0	0	0	0	59	103	0	1	17	18	0	0	0	0	0	0	0	0	5	0	7	0	6	38	0	0	5	64	12	0	0
Jul-04	2119	0	0	2	12	2	8	0	0	154	0	0	0	0	36	23	0	0	2	0	0	0	0	0	0	0	0	0	15	43	0	0	0	0	0	2	0	261	0	0	0
Aug-04	2314	0	1	0	9	18	11	1	2	763	11	2	19	23	291	269	3	0	9	1	53	0	0	0	0	0	0	0	424	117	8	40	7	158	0	0	15	181	0	12	0
Sep-04	2108	0	0	0	1	29	37	2	1	114	0	0	6	11	219	123	4	17	16	5	4	0	0	0	0	0	0	0	402	157	6	5	12	137	0	3	3	70	3	43	1
Nov-04	6853	7	4	0	11	1	4	0	0	1971	0	0	1	4	12	13	0	3	153	801	982	1	0	0	0	1	0	3	890	509	36	734	58	1312	74	41	20	1458	179	677	3
Dec-04	3327	0	0	0	0	0	0	0	0	1409	0	1	0	0	7	0	0	0	100	788	305	1	0	0	0	0	0	0	533	371	13	110	52	577	32	29	35	356	19	57	11
Jan-05	1473	980	1327	950	2234	0	2	0	0	648	1083	577	1716	1415	10	20	0	0	351	468	374	3	1	4	0	0	0	1	170	225	34	27	25	325	86	31	26	128	20	21	0
Feb-05	1269	105	64	212	81	0	0	0	0	751	12	41	21	26	0	0	0	0	113	275	88	0	0	0	0	0	0	0	316	149	14	322	0	324	13	14	34	19	0	0	0
Mar-05	879	140	29	389	49	0	0	0	0	684	0	1	8	3	0	20	0	6	152	186	3	0	0	0	0	0	0	0	88	194	4	273	2	57	50	42	26	208	3	1	0
Apr-05	702	281	59	264	160	0	0	0	0	297	0	4	7	4	0	0	0	0	65	234	0	0	0	0	0	0	0	0	35	32	22	3	0	29	0	4	13	175	30	13	0
May-05	892	82	8	20	0	0	0	0	0	258	3	3	24	0	0	0	0	0	53	11	0	0	0	0	0	0	0	0	49	35	13	0	0	12	0	12	53	73	0	0	0
Jun-05	326	82	46	43	63	0	0	0	0	106	12	0	10	0	0	0	0	0	34	3	0	0	0	0	0	0	0	0	69	23	3	0	0	46	10	17	0	23	0	0	0
Jul-05	316	72	199	27	146	0	0	0	0	34	1	0	1	0	0	0	0	0	71	23	0	0	0	0	0	0	0	0	126	157	11	0	0	0	35	4	0	14	12	0	0
Aug-05	501	16	39	62	149	0	0	0	0	89	0	0	0	0	0	0	0	0	215	31	35	1	0	1	0	1	0	0	188	66	4	166	0	0	6	0	0	5	0	25	0
Sep-05	592	56	330	118	169	0	0	0	0	198	0	0	0	0	0	0	0	0	121	70	91	0	0	0	0	0	0	0	128	82	21	92	13	38	97	2	0	2	2	0	0
Nov-05	3837	0	0	1	0	0	0	0	0	896	0	0	1	0	1	0	0	0	171	421	3427	4	0	8	0	4	1	2	268	309	20	1513	39	255	2146	18	14	28	2	454	33
Dec-05	729	0	0	0	0	0	0	0	0	658	0	0	0	0	0	0	0	0	198	781	844	0	0	6	1	2	3	0	29	110	12	410	8	69	592	0	14	66	0	108	0
Jan-06	1337	2	0	1	20	314	398	19	8	811	0	0	0	0	107	319	166	671	340	973	829	0	0	0	458	566	366	813	27	221	13	608	13	249	382	28	6	27	1	179	0
Feb-06	367	0	0	0	0	55	45	15	7	212	0	0	0	0	2	9	0	5	157	111	381	0	0	0	65	53	3	27	0	155	0	283	0	119	8	59	0	9	0	218	0
Mar-06	240	0	0	0	5	33	31	1	3	88	0	0	0	0	4	0	11	29	76	76	98	0	0	0	15	4	11	2	12	179	0	0	0	38	22	5	0	4	0	0	0

Apr-06	146	0	0	0	0	56	29	0	0	219	0	0	0	1	0	14	0	0	70	69	2	0	0	0	11	0	0	0	35	464	4	235	0	53	0	10	12	51	0	0	0
May-06	113	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	17	63	0	656	0	15	0	0	0	0	0	11	0
Jun-06	52	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	117	130	3	68	0	14	0	0	0	0	0	0	0
Jul-06	220	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	19	19	0	0	0	0	0	0	0	0	296	72	0	731	0	0	0	0	0	0	0	31	0
Aug-06	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	109	22	2	0	0	0	0	0	0	2	526	160	1	565	0	5	0	0	0	37	0	76	0
Sep-06	106	0	1	0	2	1	3	0	0	108	0	0	0	0	0	0	0	0	217	4	0	0	0	0	0	0	0	0	553	278	2	382	0	12	0	0	1	4	0	37	0
Nov-06	1220	1	1	2	3	0	0	0	0	860	0	0	0	0	0	0	0	0	1588	623	687	0	0	1	0	0	0	1	750	362	2	5131	3	99	41	8	6	3	3	662	1
Dec-06	83	0	0	0	0	2	0	0	0	179	0	0	0	0	0	0	0	0	298	882	141	0	0	0	0	0	0	0	481	131	2	919	1	113	25	10	0	0	5	225	0

15.3 Catch rates and fishing power

Catch rates are shown in the model output goodness of fit in Appendix 5 (Section 16.1). For more details on the catch rate standardisation procedure and fishing power analysis see O'Neill and Leigh (2006) and Campbell *et al.* (2010).

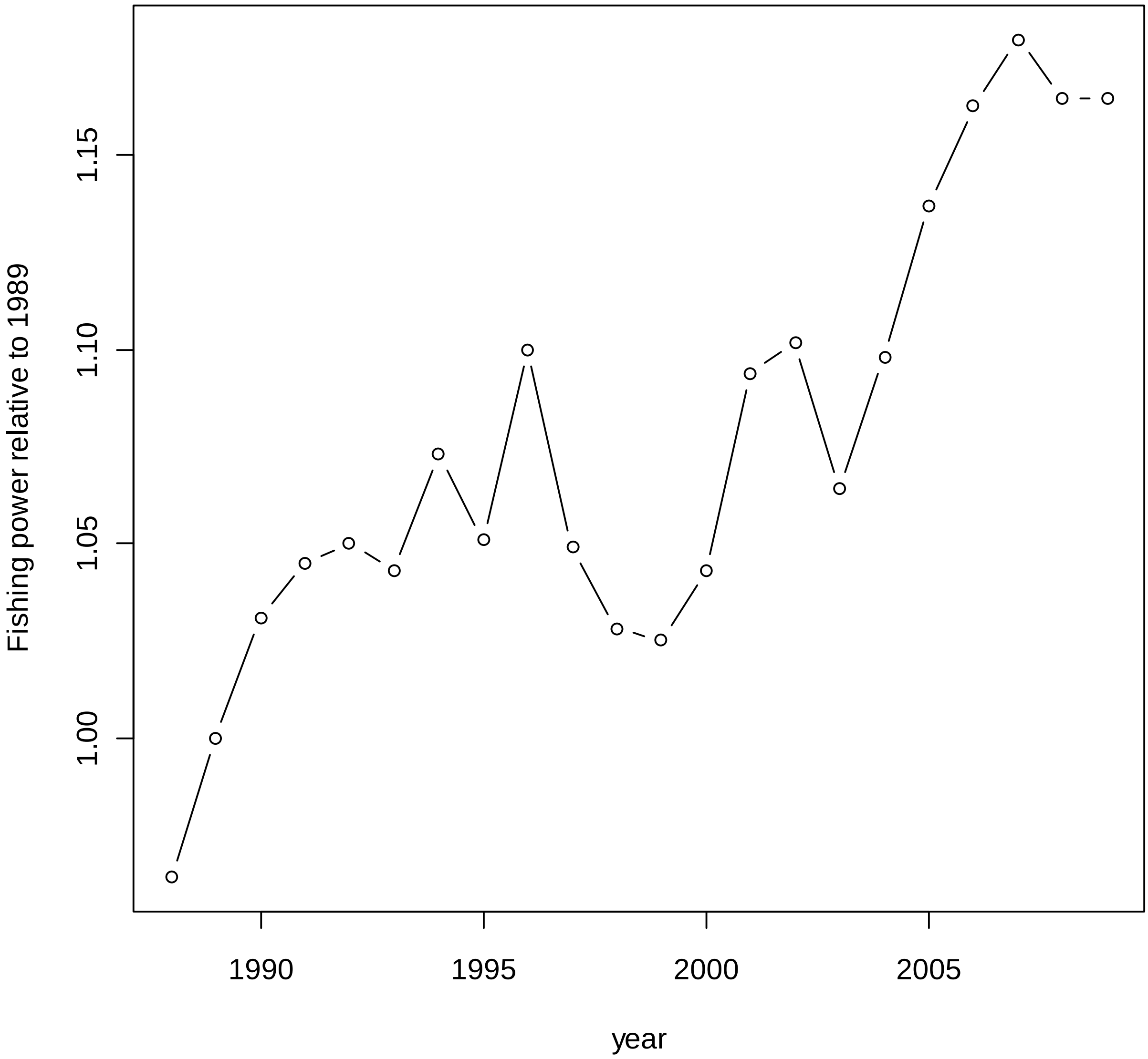

Figure 6 Fishing power relative to 1989.

15.4 Biological

Parameters	Estimates	Data Sources
von Bertalanffy Scallop Growth		
l_∞, k	106.026 SH mm; 0.225 month^{-1}	(Williams and Dredge 1981)
Shell Height (mm) to Weight		
$w_{grams} = aSH^b$		
a, b	1.26E-09, 3.485	FRDC2000/170, 2003 LTMP, QFS, 2003
Relative Meat Weight Condition (Proportional relative to October)		Dredge (unpublished)
November	1.08	
December	1.17	
January	1.17	
February	1.25	
March	1.17	
April	1.08	
May	1.00	
June	0.83	
July	0.83	
August	0.83	
September	0.92	
October	1.00	
Natural Mortality (M)	0.09	(Dredge 1985)
Shell Height (mm) to Fecundity		
$\text{fec} = aSH^b$		
a, b	3220.708 (24558), 1.354 (1.665)	(Dredge 1981)
Proportion mature at age (mat_a *)*		
a, b where	-0.794 (0.238), 0.178 (0.022)	(Dredge 1981)
$\eta = a + bAge$, and $mat_a = \dfrac{\exp\eta}{1+\exp\eta}$		
Monthly Spawning Pattern (Proportion, β)		
November	0.0072	(Dredge 1981)
December	0.0000	
January	0.0144	
February	0.0288	
March	0.0899	
April	0.1331	
May	0.1403	
June	0.1439	
July	0.1439	
August	0.1403	
September	0.0863	
October	0.0719	

15.5 Selectivity

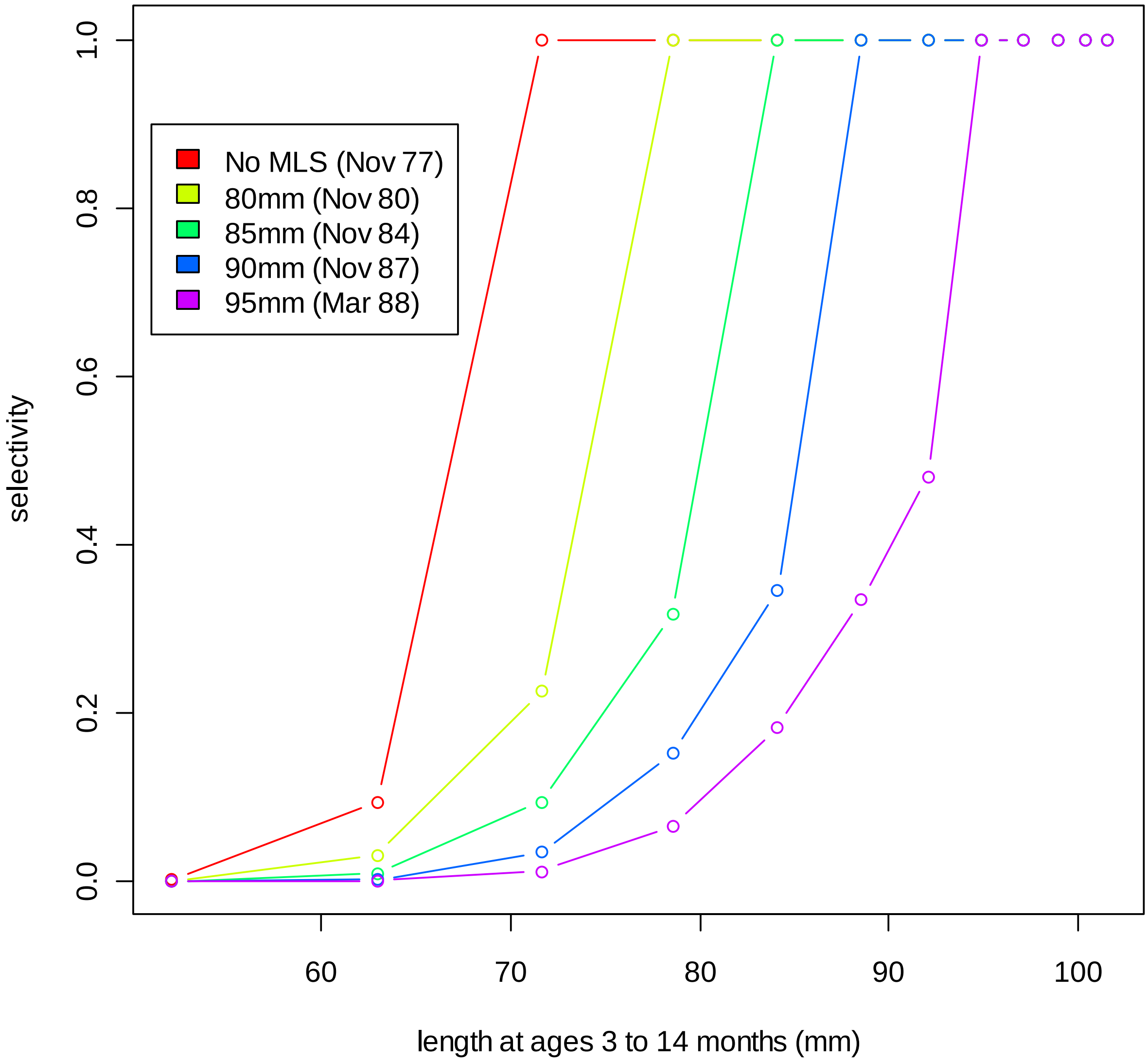

Figure 7 Selectivity curves used in the model.

The history of selectivity curves used in the model is as follows:

- Nov 1977 to Oct 1980: red curve
- Nov 1980 to Oct 1984: yellow curve
- Nov 1984 to Oct 1987: green curve
- Nov 1987 to Dec 1999: blue curve Nov to Apr, purple curve May to Oct
- Jan 2000 to Oct 2004: blue curve Jan to Apr, purple curve May to Dec
- Nov 2004 to Oct 2009: blue curve Nov to Apr, purple curve May to Oct
- Current (Nov 2009 onwards, equilibrium simulation scenarios 1 and 2): blue curve all year
- Equilibrium simulation scenario 3: blue curve Nov to Apr, purple curve May to Oct

15.6 Spatial recruitment index

Table 15 Logarithm of the average scallop density (in number of zero-plus per square metre) for all cells with more than two observations, based on the scallop fishery independent survey conducted between 1997 and 2006, in October.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Oct-97	-6.57	NA	-4.65	-5.55	-4.94	-3.95	-6.88	-11.00	-11.00	-5.35	-5.37	-5.30	-5.56	-3.70	-5.10	-3.50	NA	NA	-6.01	-5.96	-6.00	-2.05
Oct-98	-8.26	-7.45	-1.00	-7.93	-4.98	-4.17	-5.84	-8.47	-8.01	-6.11	-4.63	-5.53	-4.96	-5.46	-5.30	-4.00	-6.23	-4.98	-7.02	-7.70	-6.38	-6.15
Oct-99	-5.95	NA	-3.28	-3.26	-3.48	-4.38	-3.83	-4.88	-6.49	-6.22	-6.60	-3.84	-6.21	-6.45	-5.17	-5.73	-6.80	NA	-7.90	-8.76	-7.27	-5.27
Oct-00	-6.61	NA	-6.14	-2.74	-2.59	-3.51	-5.06	-5.69	-6.95	-6.30	-5.09	-4.37	-3.31	-4.03	-4.82	-4.14	NA	-4.82	-6.70	-6.33	-4.26	-3.62
Oct-01	NA	-5.59	-7.95	-5.90	-7.64	-7.01	-5.35	-8.88	-6.80	-5.74	-5.77	-4.85	-4.02	-3.07	-4.66	-3.73	-4.38	-4.53	NA	NA	-4.92	-4.23
Oct-02	-5.13	-6.42	-7.23	-5.33	-5.41	-8.59	-9.07	-7.88	-10.48	-6.18	-5.62	-4.57	-4.77	-7.01	-5.48	-4.25	-5.08	-5.05	NA	-4.60	-4.50	-2.24
Oct-03	NA	-5.50	-4.36	-4.47	-3.74	-5.06	-7.73	-6.29	-9.67	-5.78	-4.63	-3.83	-4.41	-3.54	-3.64	-3.56	-4.16	-4.95	NA	NA	-4.25	-4.41
Oct-04	NA	-3.99	-4.66	-2.71	-4.53	-4.72	-5.06	-7.38	-6.15	-5.90	-5.91	-4.47	-4.42	-5.13	-3.57	-4.48	-6.89	-4.25	NA	NA	-3.96	-4.44
Oct-05	NA	-5.22	-7.66	-5.73	-4.66	-8.49	-7.09	-9.55	-8.90	-6.90	-6.07	-4.32	-4.30	-4.17	-5.38	-5.30	-5.79	-6.21	NA	NA	-2.40	-3.77
Oct-06	NA	-5.65	-5.86	-6.32	-7.01	-8.40	-8.03	-8.66	-8.54	-6.65	-5.55	-5.92	-4.21	-4.12	-4.17	-4.51	-5.88	-4.98	NA	NA	-2.42	-4.76

	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Oct-97	-3.31	-4.51	-5.42	-6.08	-5.81	-6.14	-7.70	-9.34	-6.12	NA	-6.63	-6.13	-6.20	-4.90	-4.67	NA	NA	NA	NA	-6.31	-3.79
Oct-98	-5.17	-4.86	-6.73	-3.62	NA	-4.22	-8.15	-9.59	-9.30	NA	-6.36	-7.99	-7.03	-6.36	-5.78	NA	NA	NA	NA	-7.03	-8.36
Oct-99	-6.76	-4.88	-6.67	-8.30	-6.95	-7.41	-8.14	-8.46	-9.53	NA	-6.35	-6.70	-8.59	-4.53	-5.09	NA	NA	NA	NA	-6.80	-5.64
Oct-00	-4.22	-4.85	-3.77	-4.86	-3.63	-4.83	-7.48	-7.29	-9.16	NA	-5.81	-4.69	-5.27	-5.15	-3.76	NA	NA	NA	NA	-4.22	-3.81
Oct-01	-2.12	-4.00	-6.05	-4.77	-5.98	-4.83	NA	NA	NA	NA	NA	NA	NA	-4.72	NA	NA	NA	NA	NA	NA	-2.70
Oct-02	-5.18	-3.04	-4.62	-2.39	-5.50	-2.86	NA	NA	NA	NA	-5.68	NA	-5.52	-6.76	NA	NA	NA	NA	NA	NA	-7.00
Oct-03	-5.61	-4.23	-5.20	-5.40	-5.13	-5.04	NA	NA	NA	NA	NA	NA	NA	-6.16	NA	NA	NA	NA	NA	NA	-4.98
Oct-04	-4.77	-3.56	-5.14	-4.07	-4.08	-4.20	NA	NA	NA	NA	NA	NA	NA	-7.32	NA	NA	NA	NA	NA	NA	-4.53
Oct-05	-5.39	-4.12	-4.12	-5.26	-5.59	-4.52	NA	NA	NA	NA	NA	NA	-5.61	-7.25	NA	NA	NA	NA	NA	NA	NA
Oct-06	-4.84	-4.64	-7.06	-6.04	-6.04	-5.17	NA	NA	NA	NA	NA	NA	NA	-6.90	NA	NA	NA	NA	NA	NA	-6.07

16 Appendix 4: Model Output Plots

16.1 Goodness of fit

16.1.1 Model One

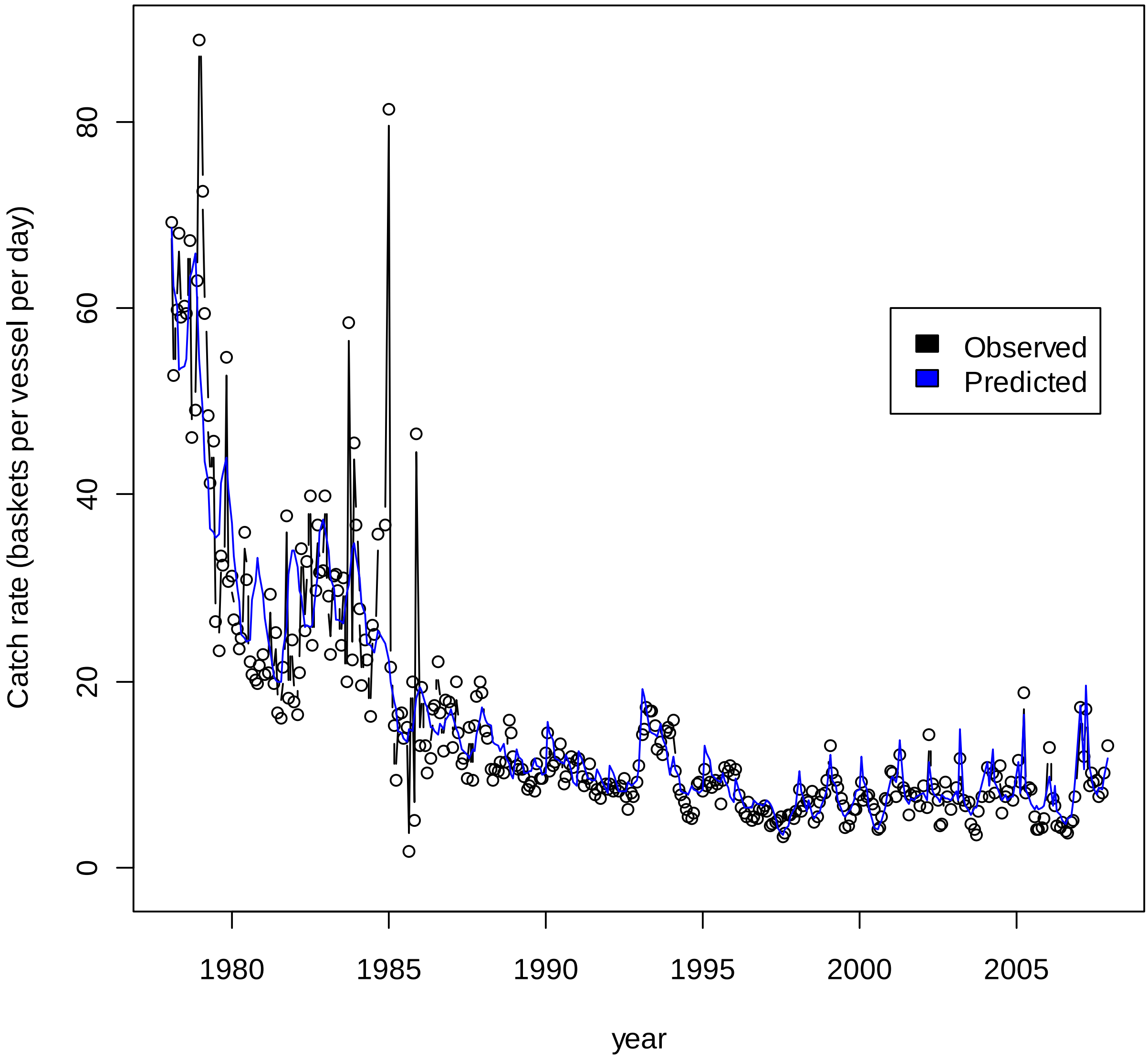

Figure 8 Long-term catch rate fit.

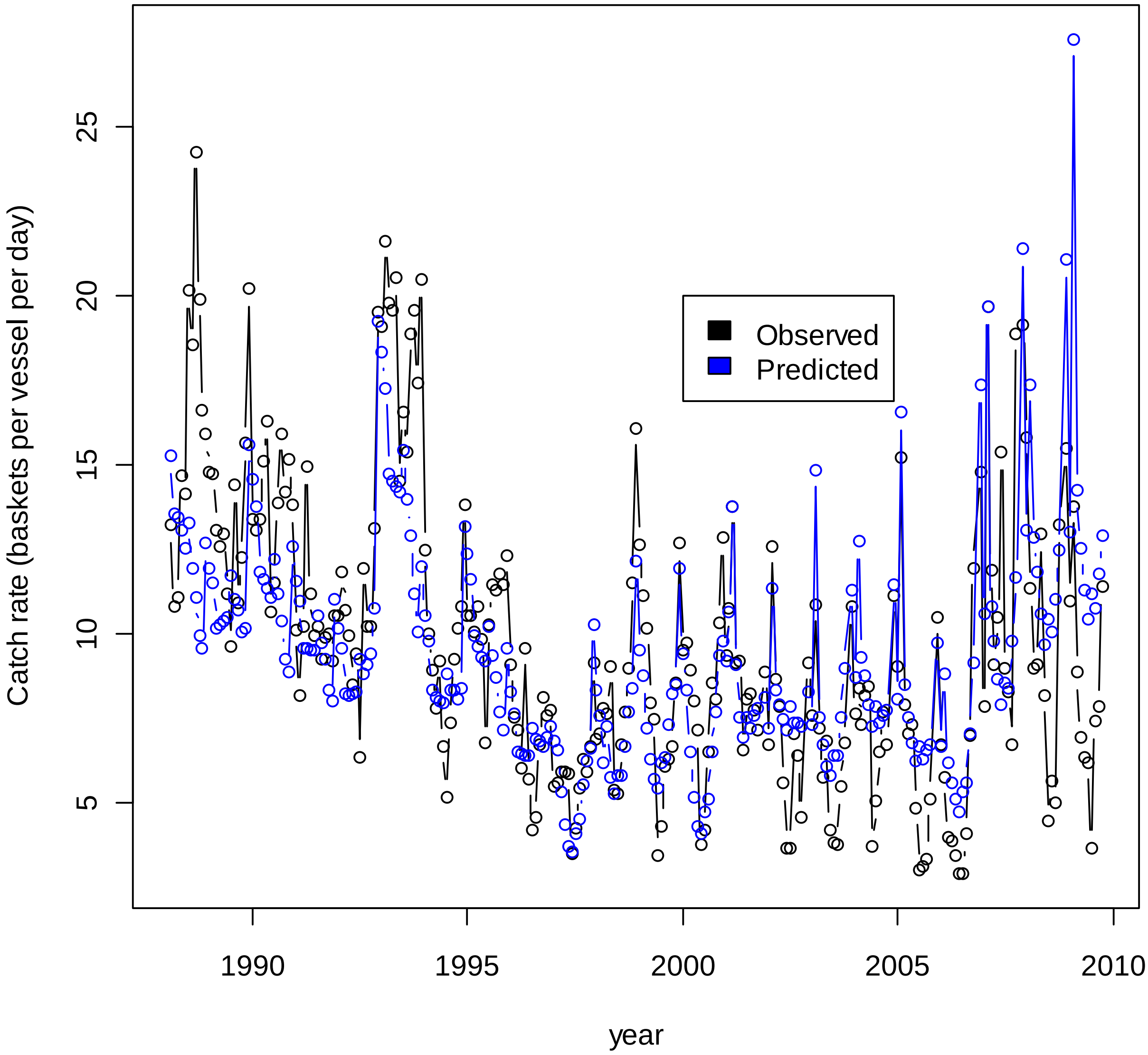

Figure 9 Short term catch rate observed and predicted. Note that this model does not actually fit to this data series, it is useful however to consider what would have been predicted. Note the clear divergence at the end of the series with predictions trending significantly higher than observed values.

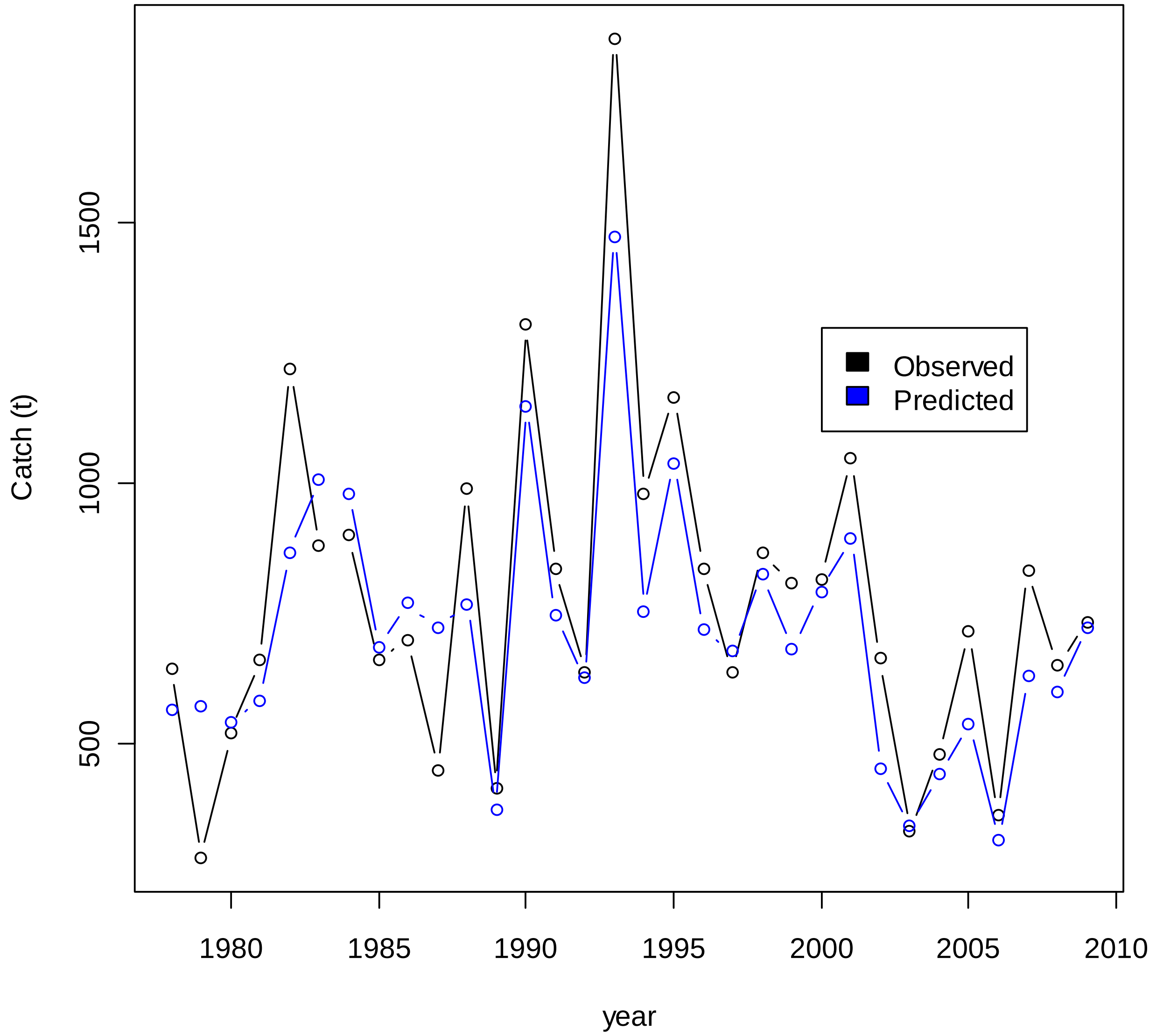

Figure 10 Full time series annual catch fit.

16.1.2 Model Two

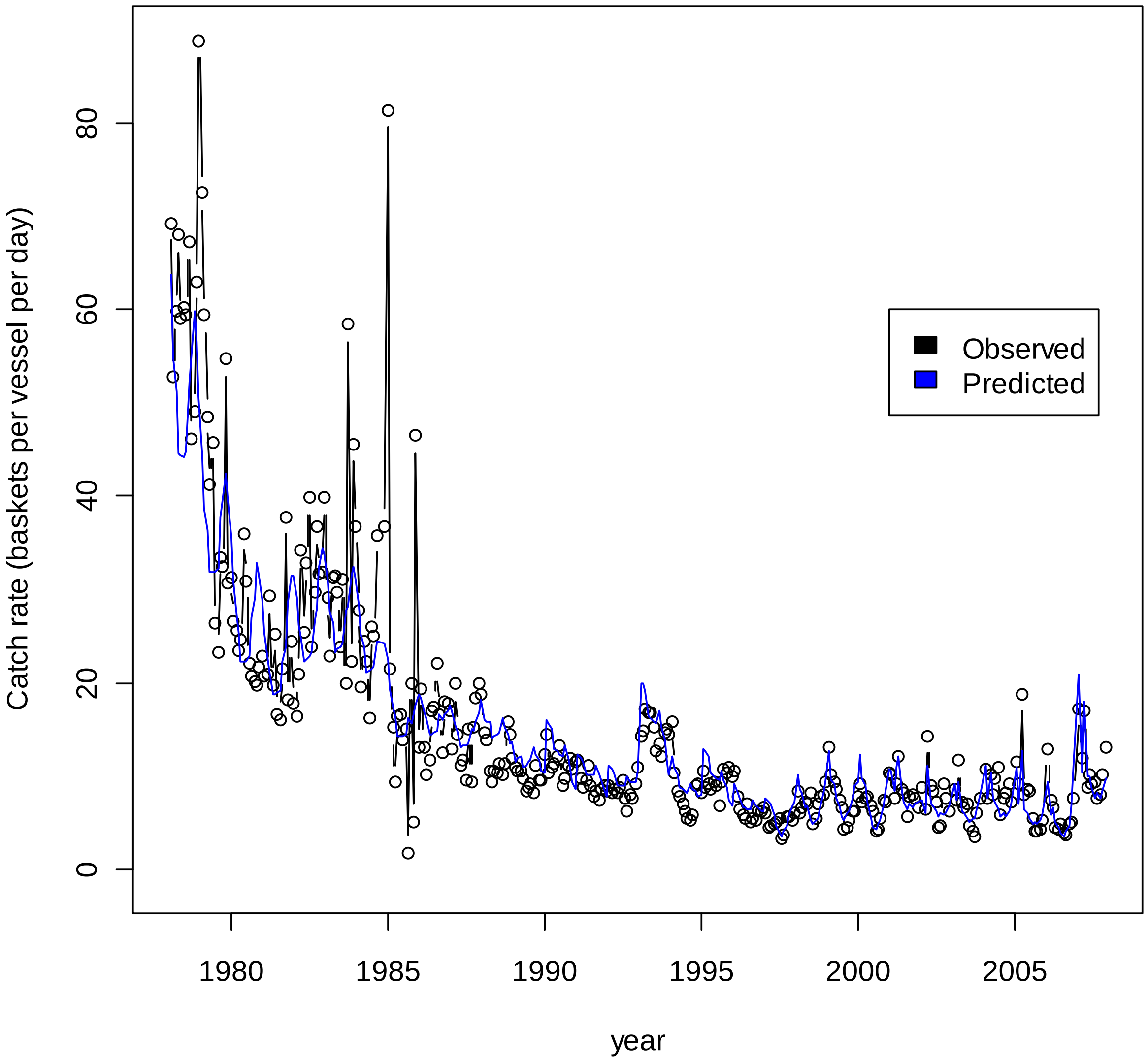

Figure 11 Long-term standardised catch rate fit.

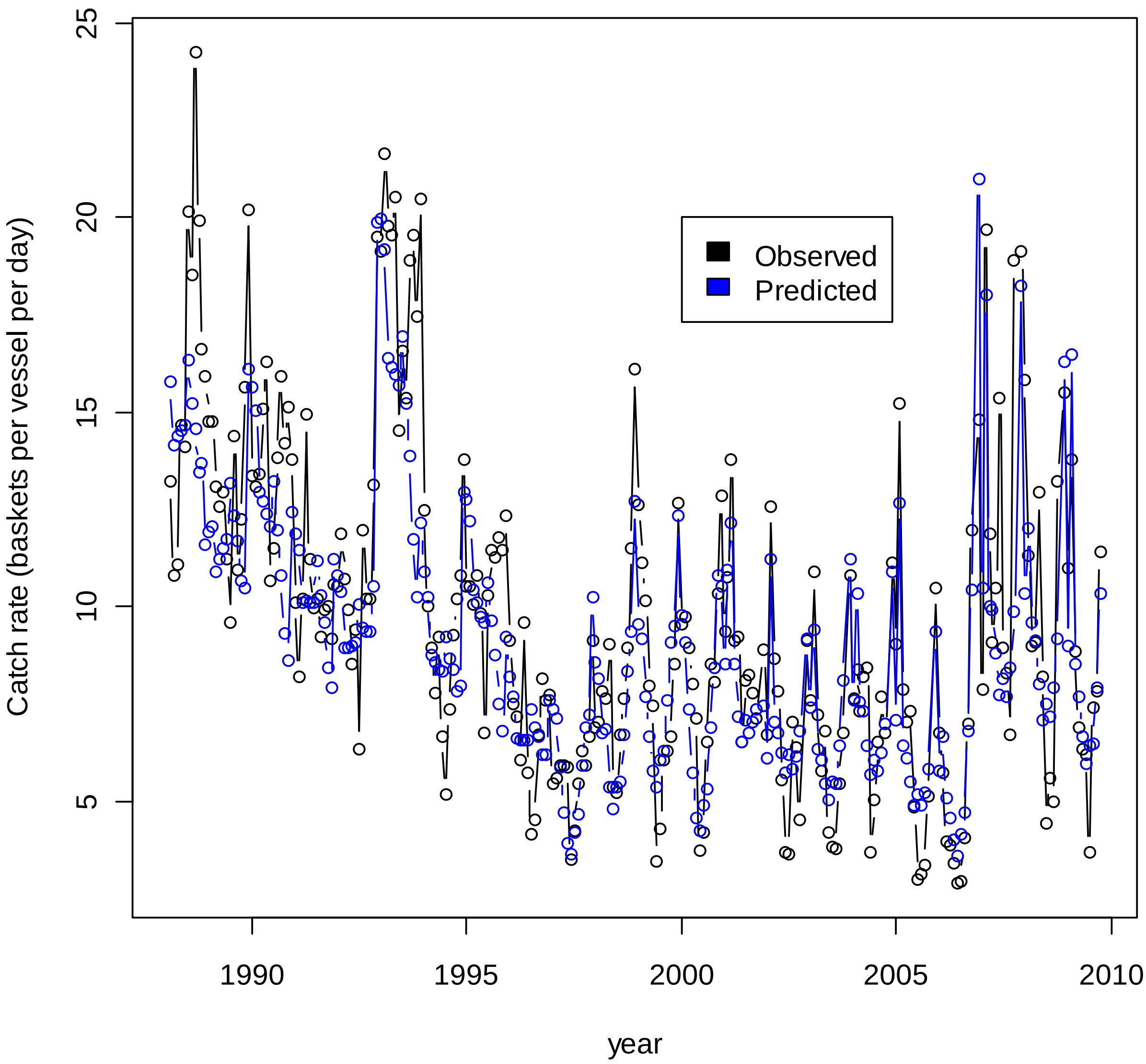

Figure 12 Short-term (Cfish) standardised catch rate fit.

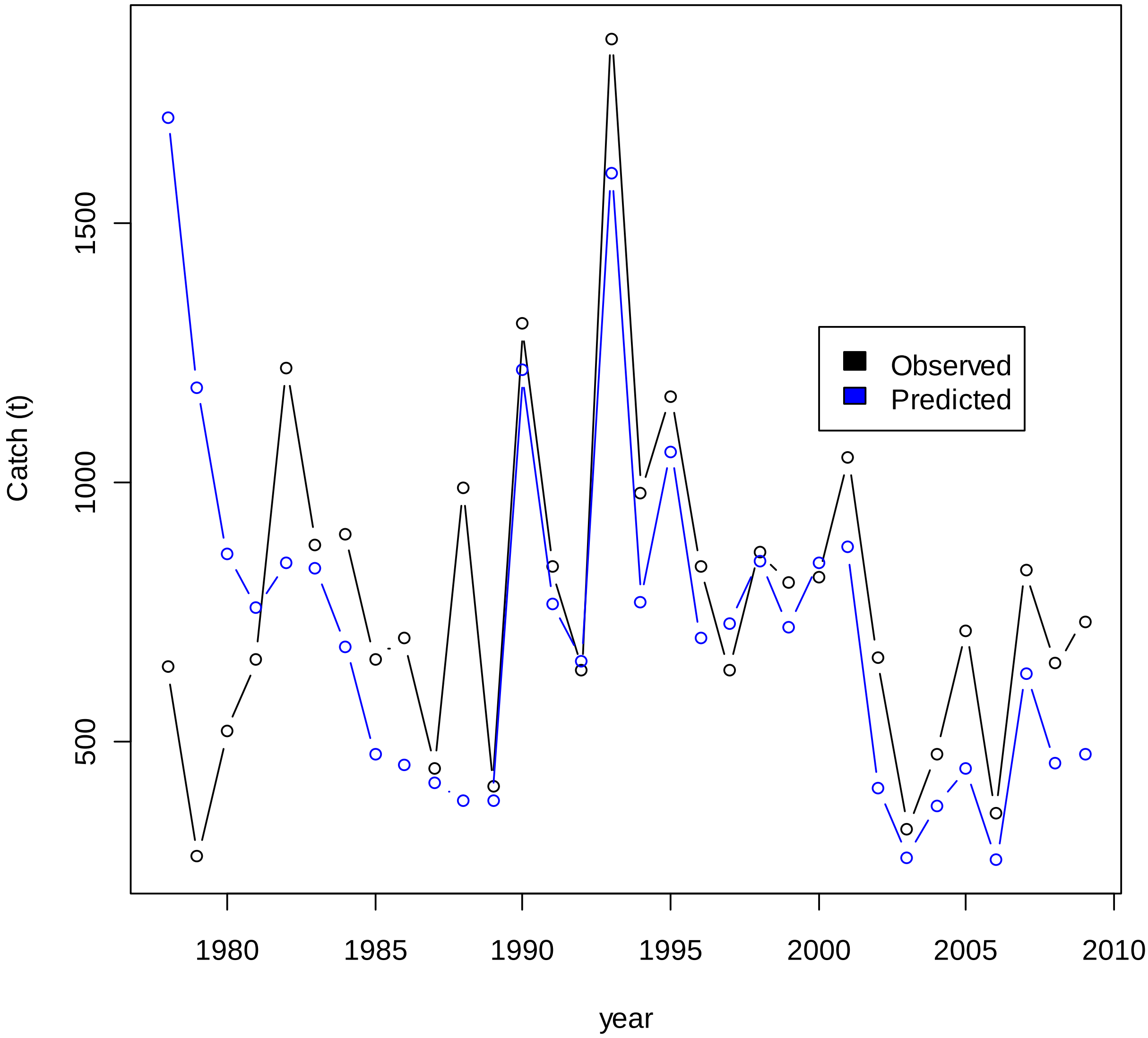

Figure 13 Full time series annual catch fit.

16.1.3 Model Three

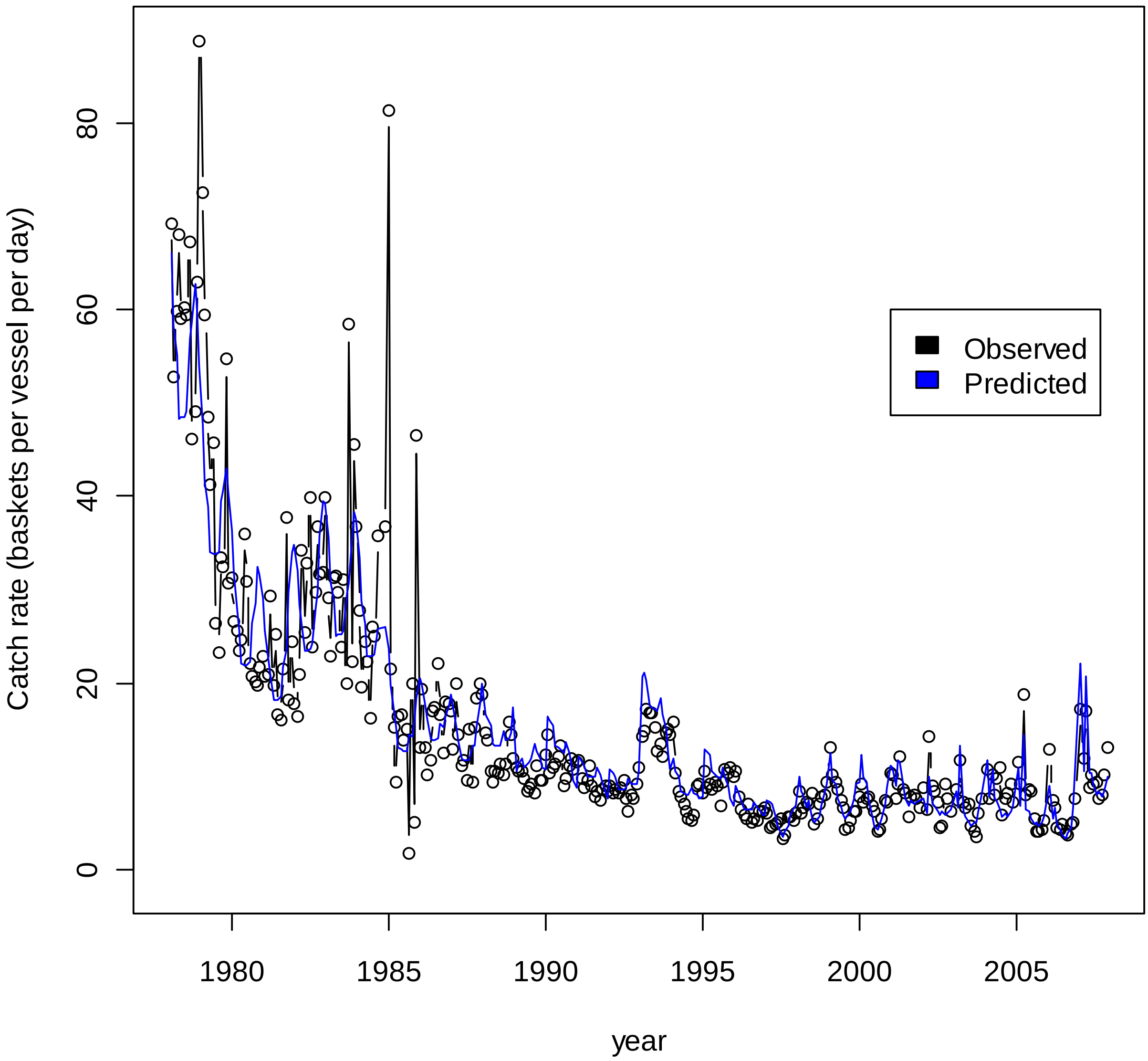

Figure 14 Long term catch rate fit.

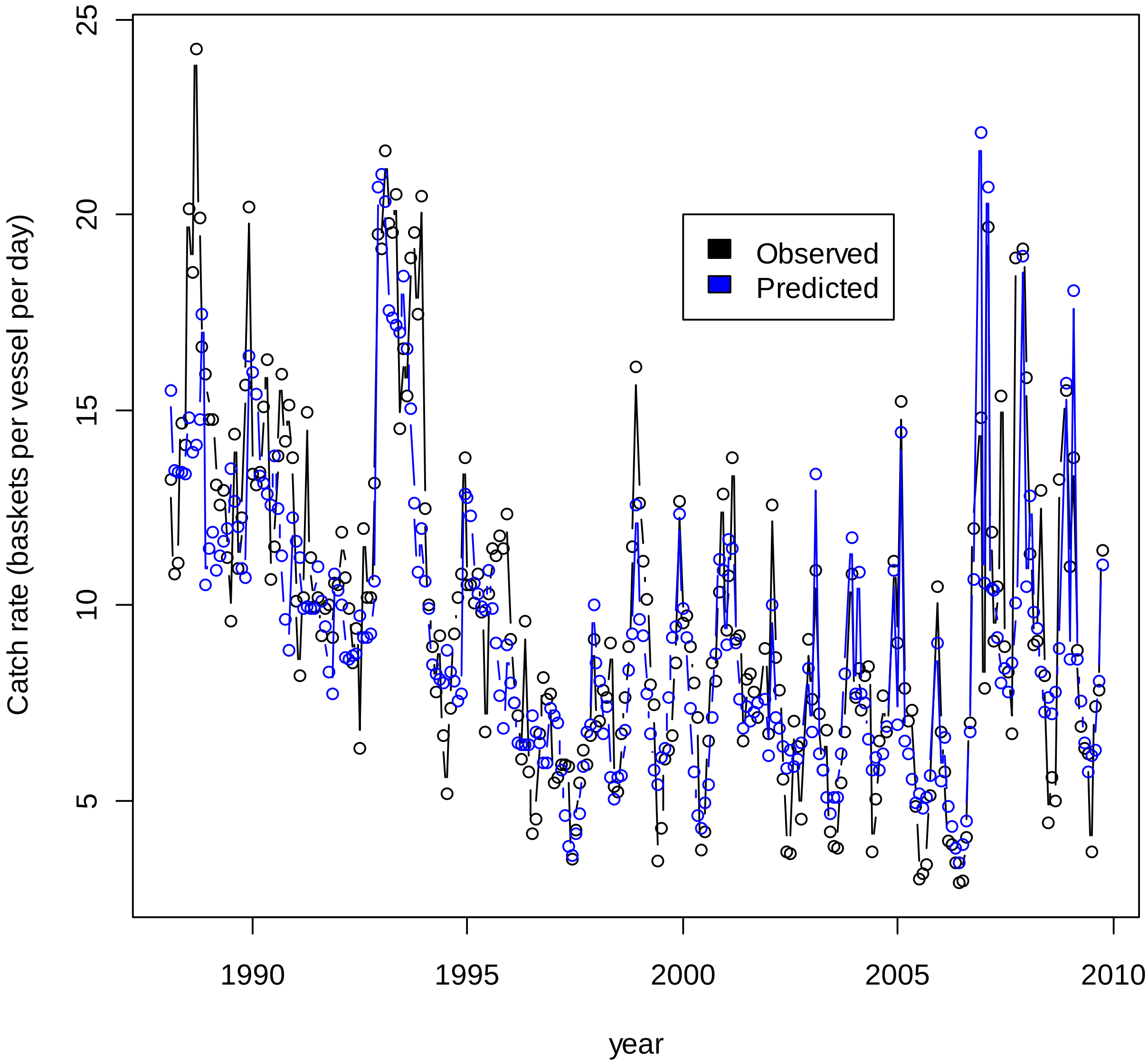

Figure 15 Short-term (Cfish) standardised catch rate fit.

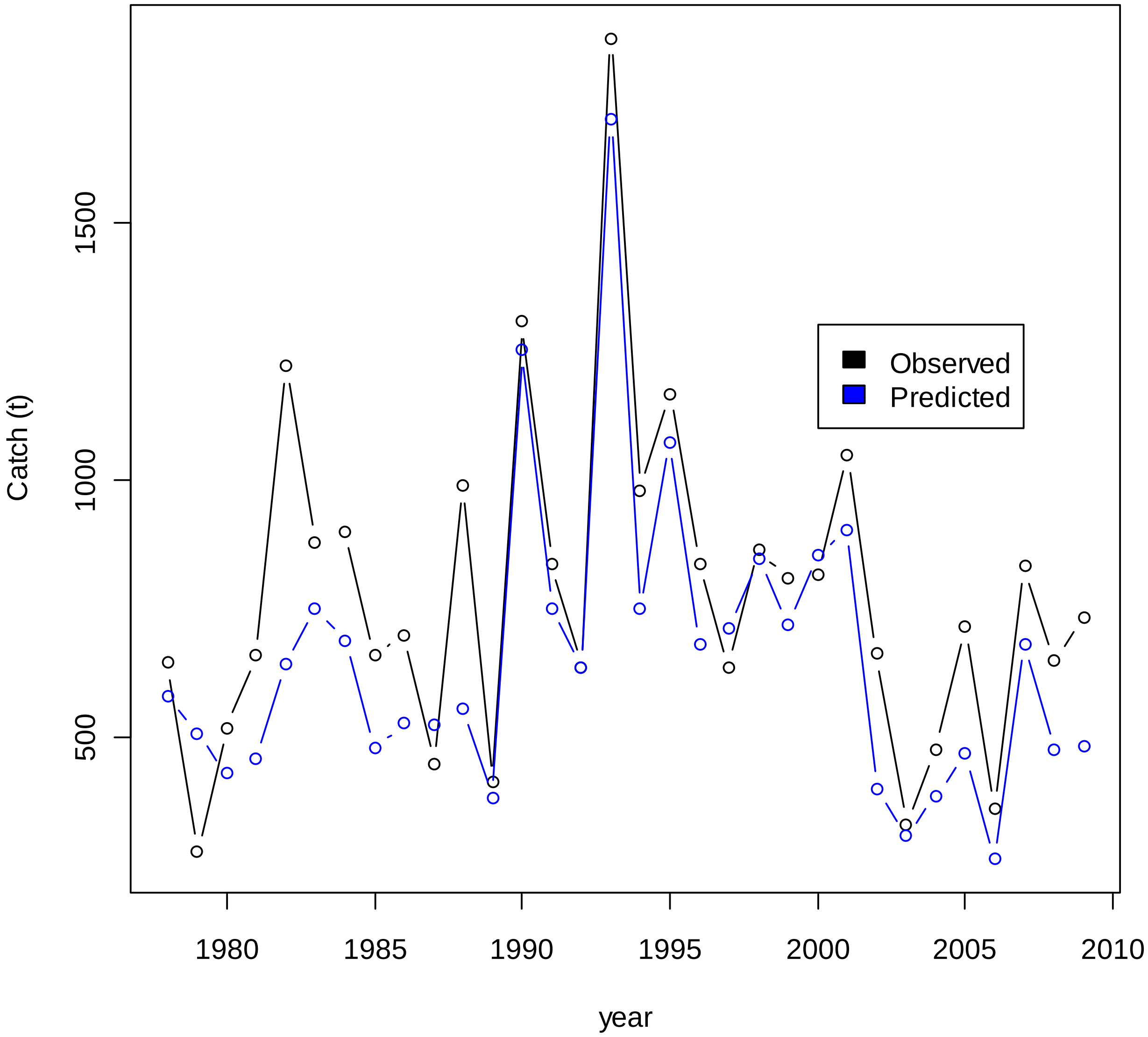

Figure 16 Full time series annual catch fit.

16.1.4 Model Four

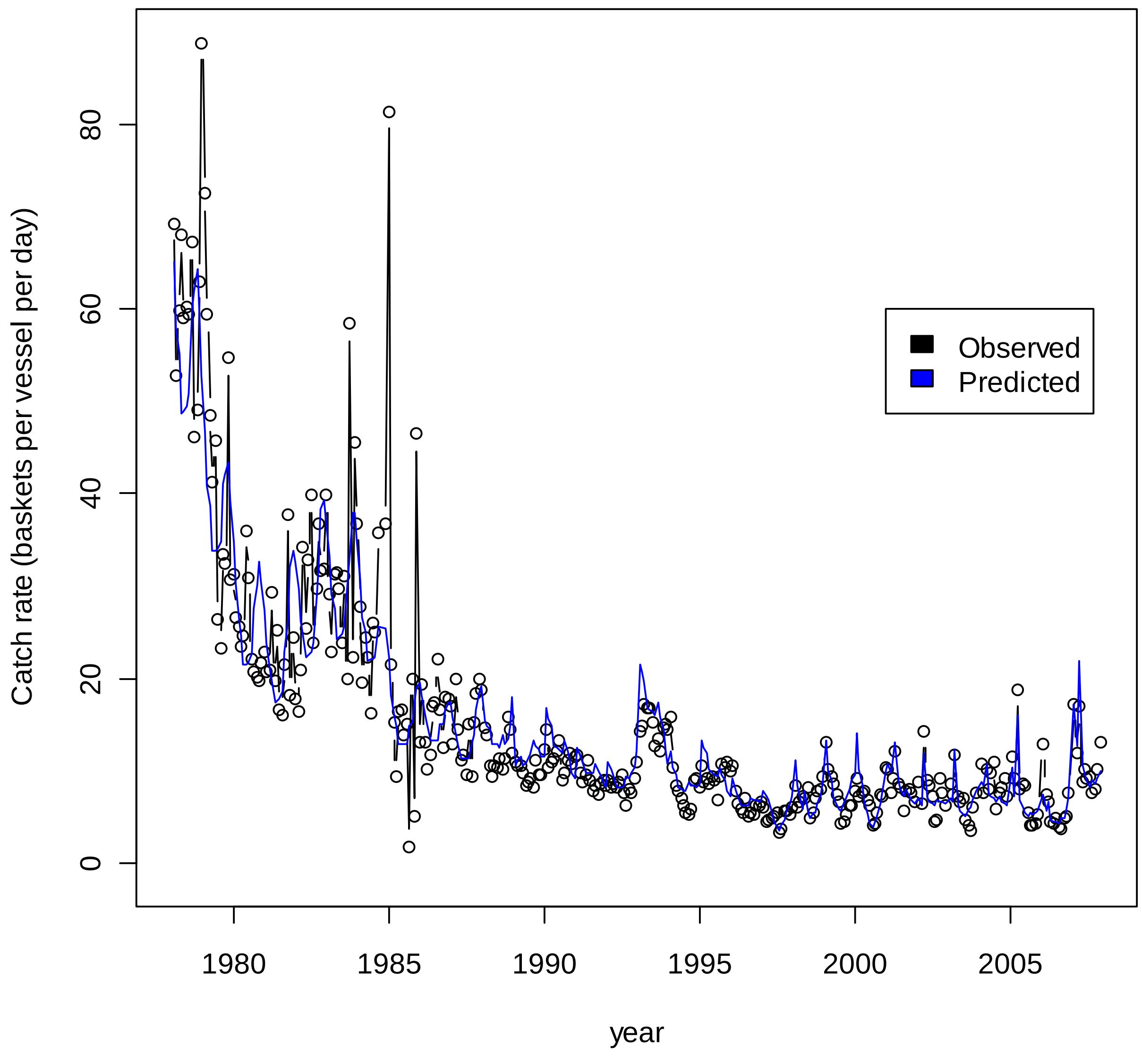

Figure 17 Long-term standardised catch rate fit.

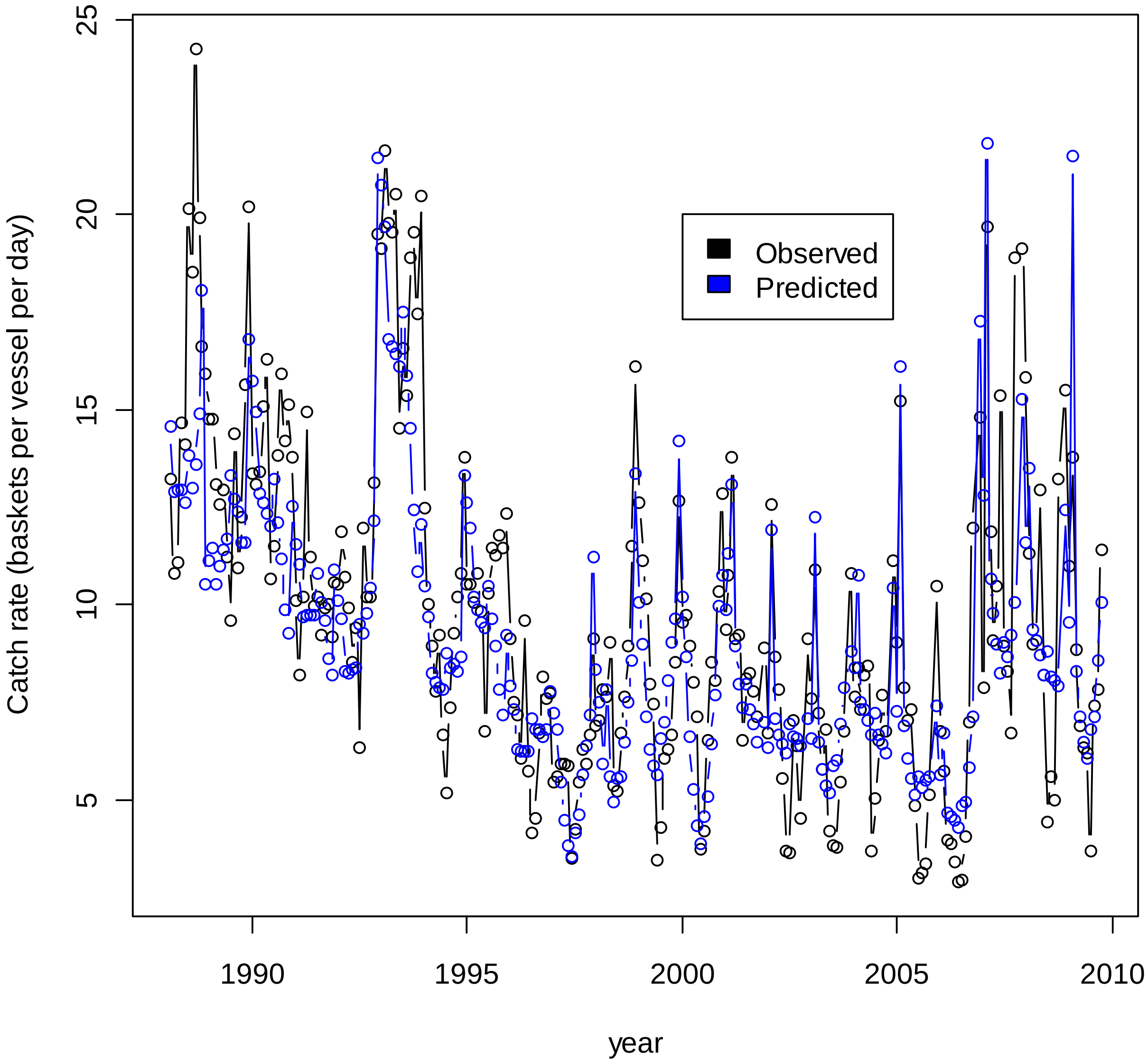

Figure 18 Short-term (Cfish) standardised catch rate fit.

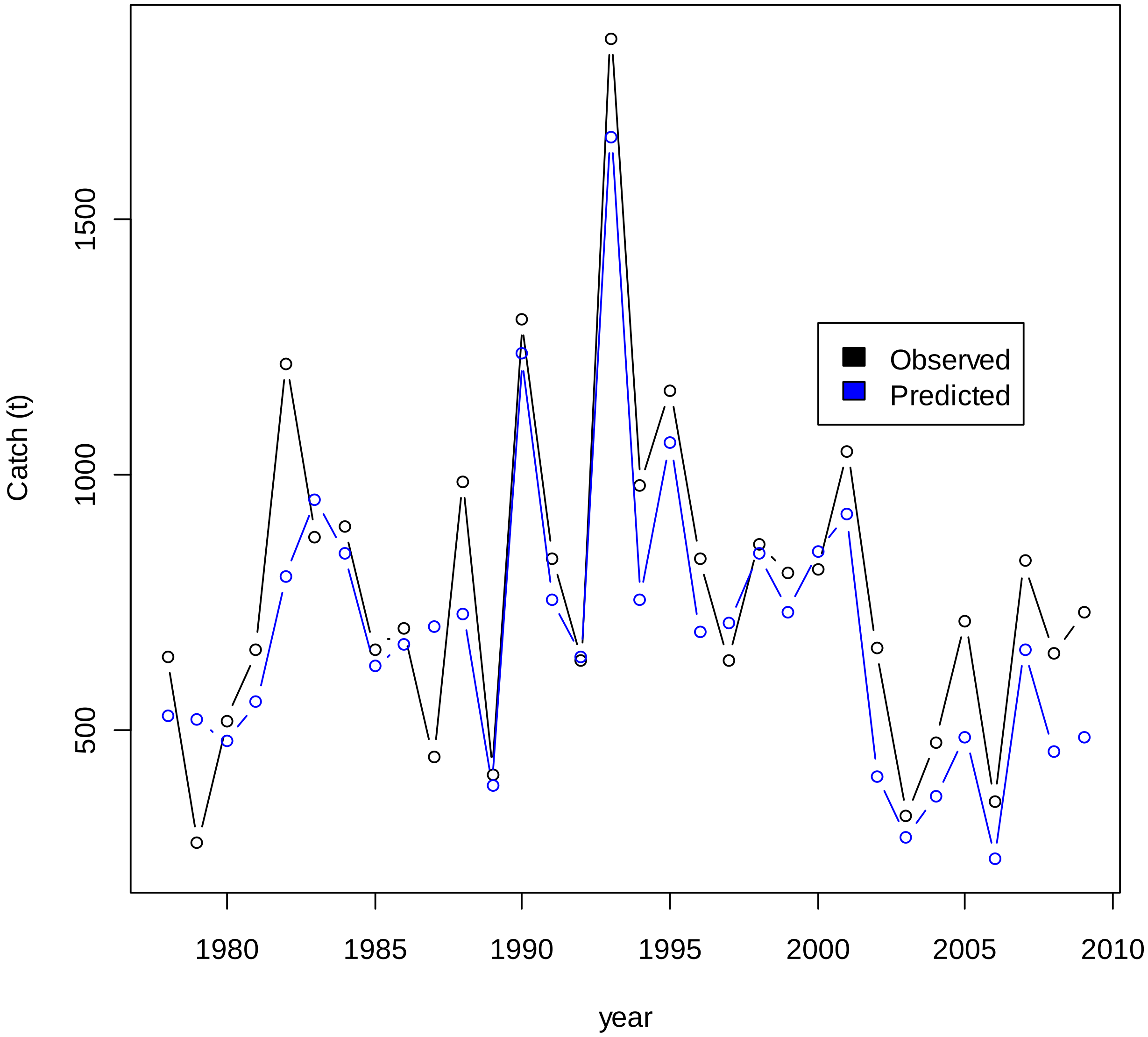

Figure 19 Full time series annual catch fit.

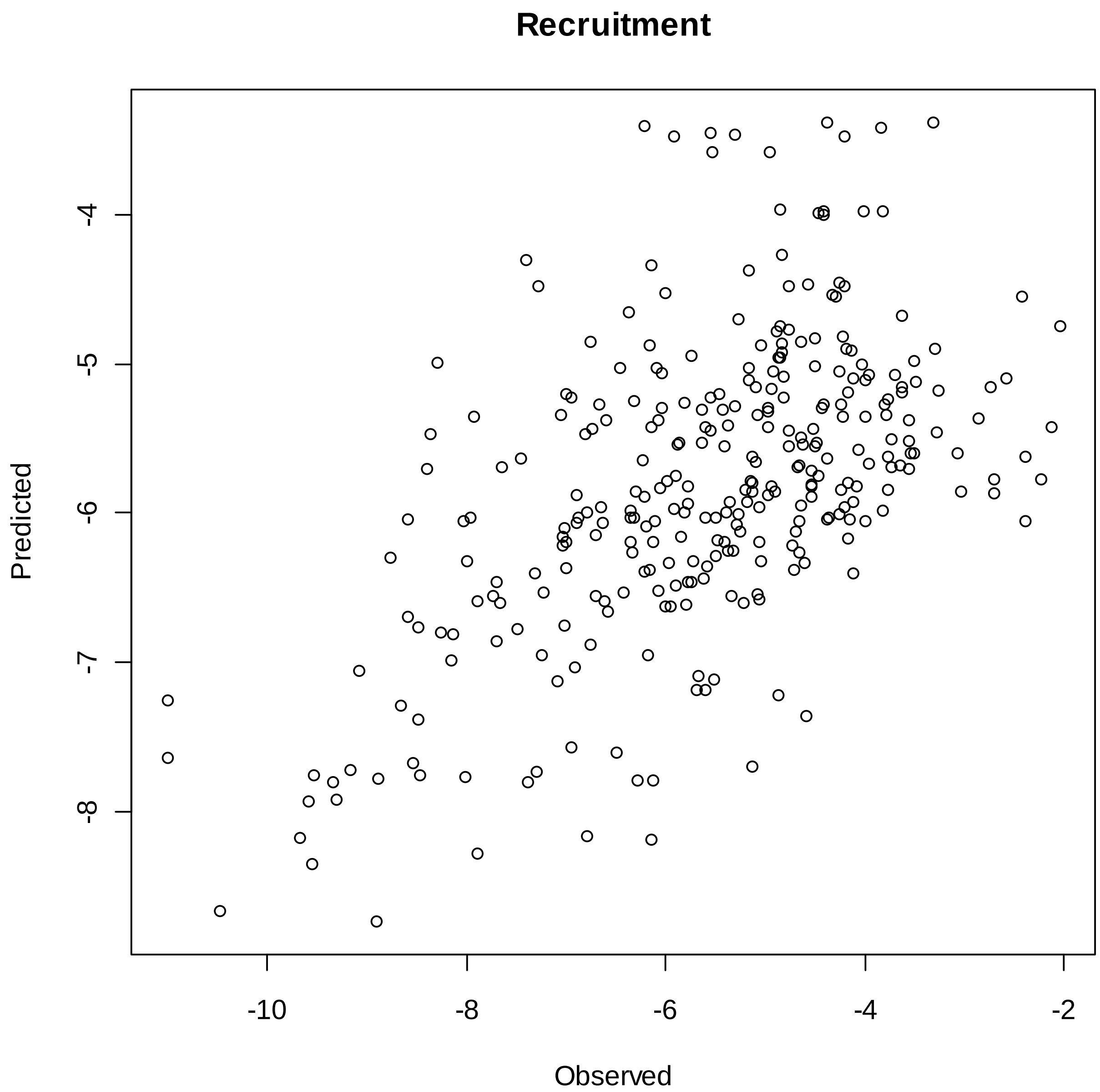

Figure 20 Recruitment index goodness of fit over space-time, spatial and temporal indices ignored.

16.2 Relative egg production since 1977

16.2.1 Model One

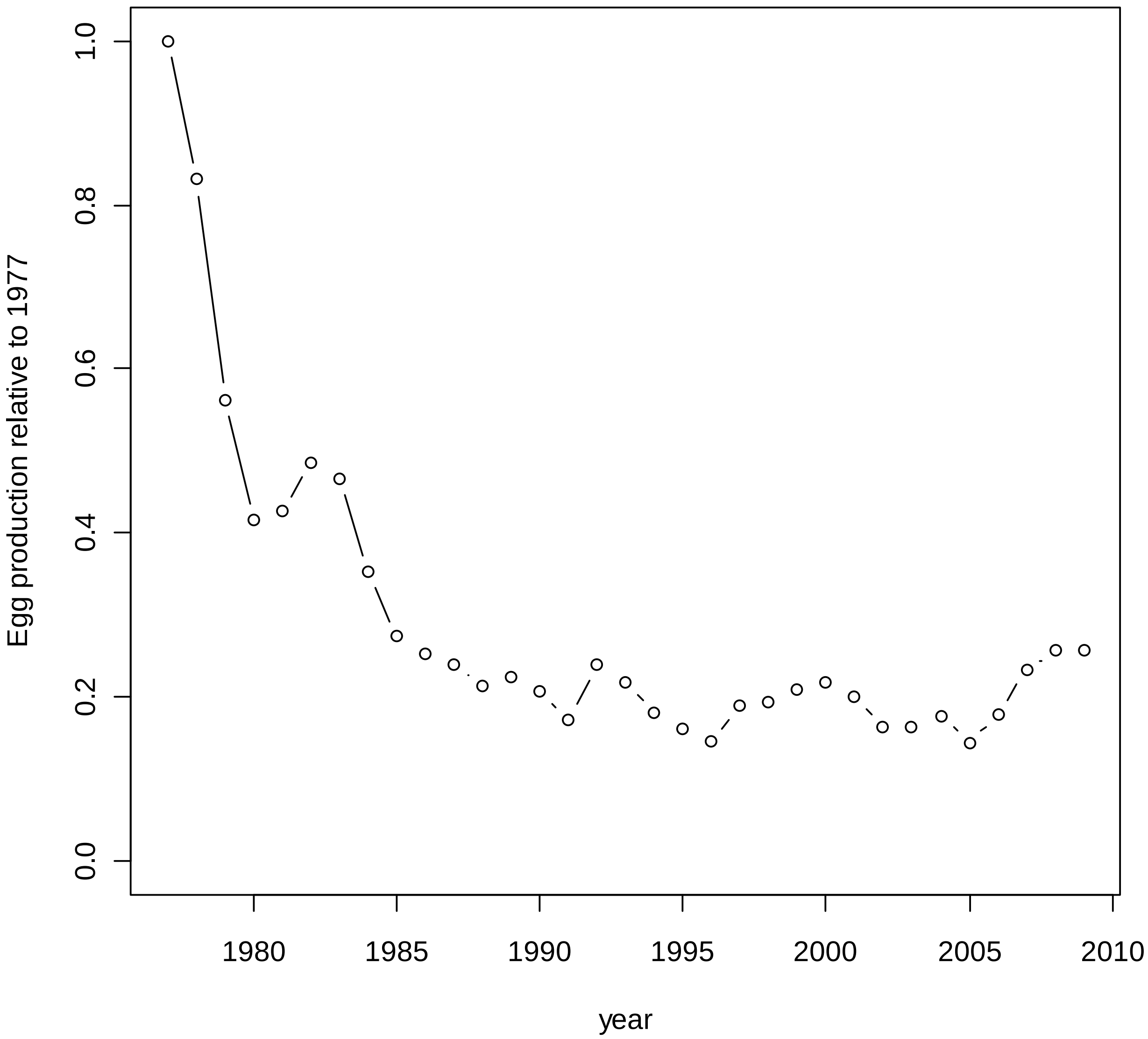

Figure 21 Egg production relative to 1977 for model one.

16.2.2 Model two

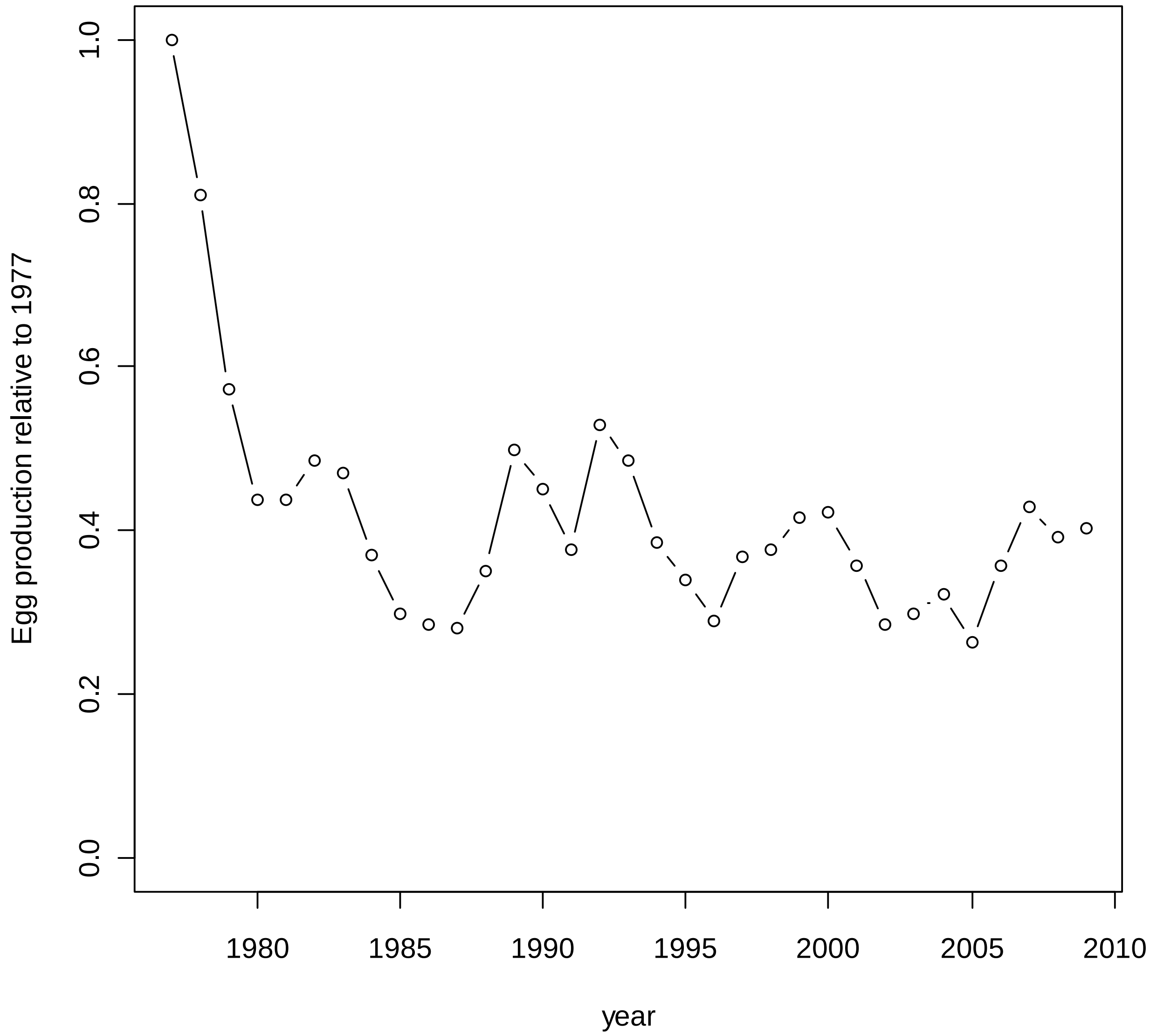

Figure 22 Egg production relative to 1977 for model two.

16.2.3 Model three

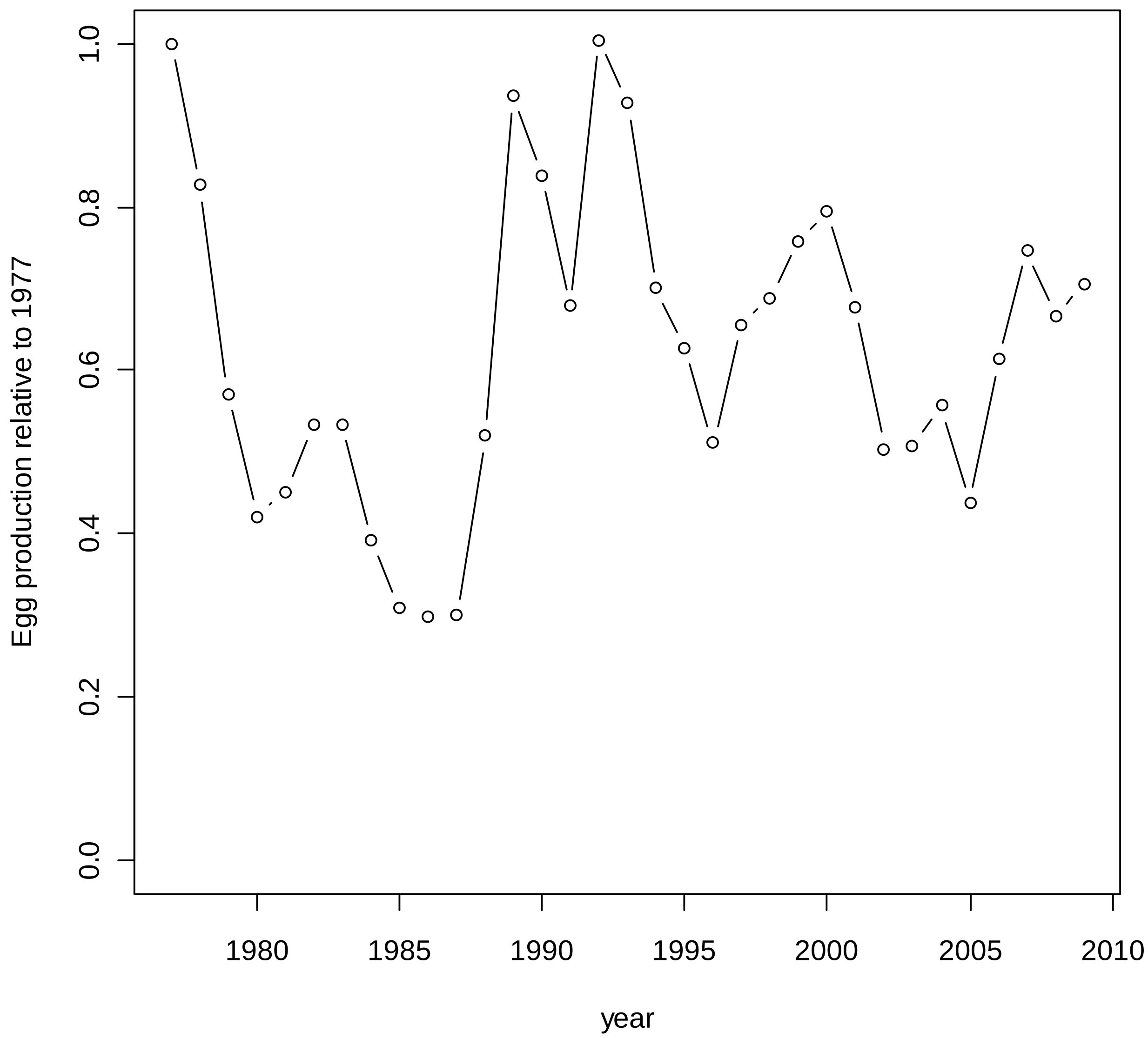

Figure 23 Egg production relative to 1977 for model three.

16.2.4 Model four

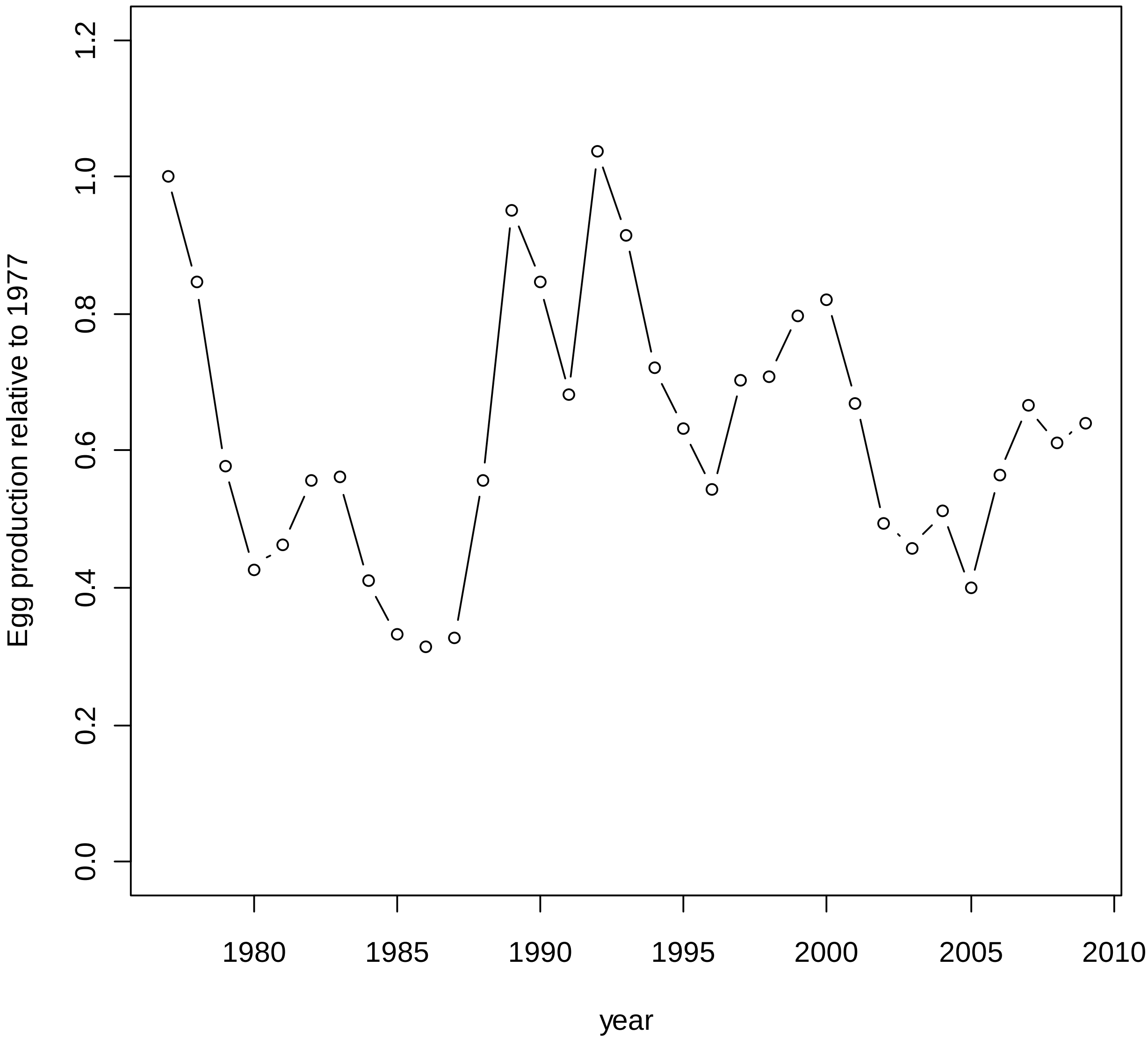

Figure 24 Egg production relative to 1977 for model four.

16.3 Spatial effects

16.3.1 Model One

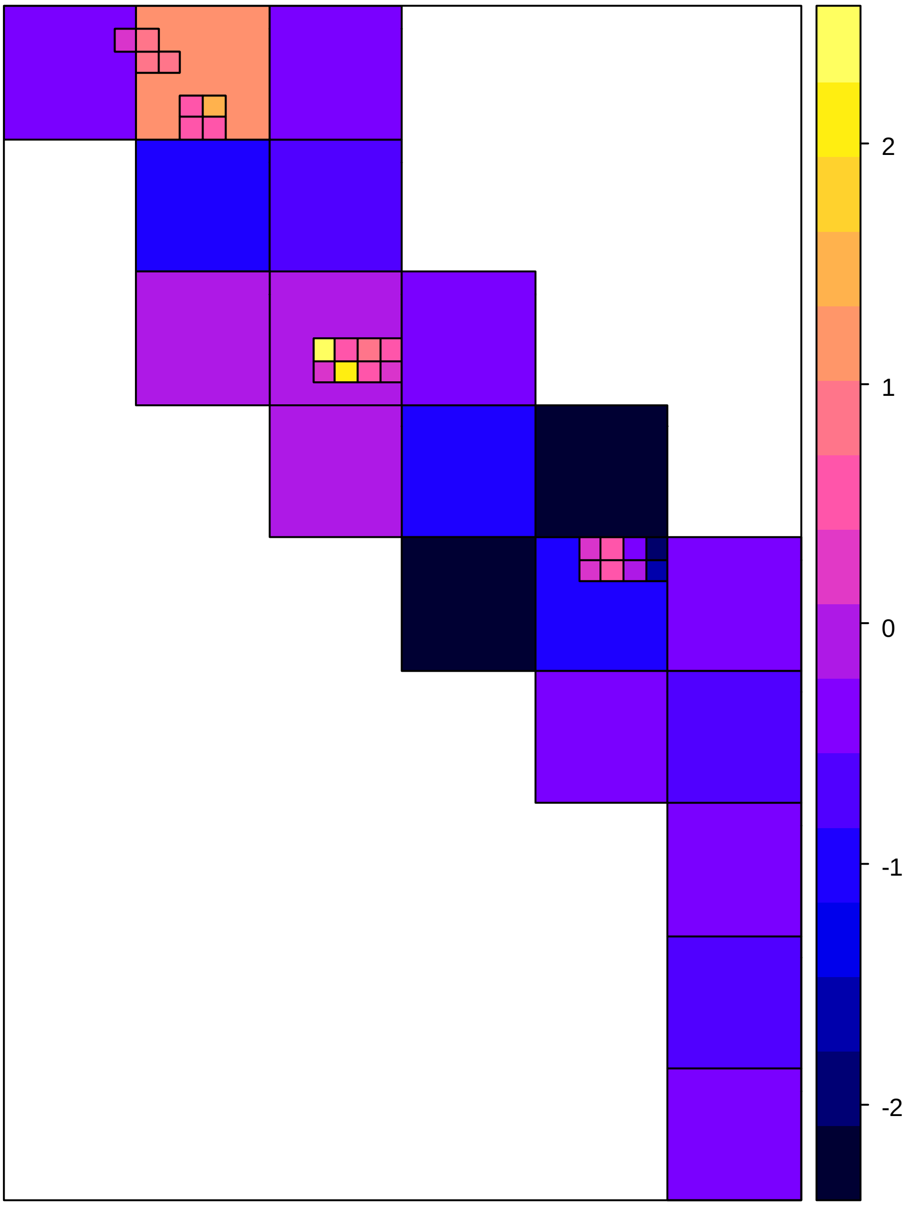

Figure 25 Posterior mode of the spatial random effect parameters, ψ_k , for model one.

16.3.2 Model Four

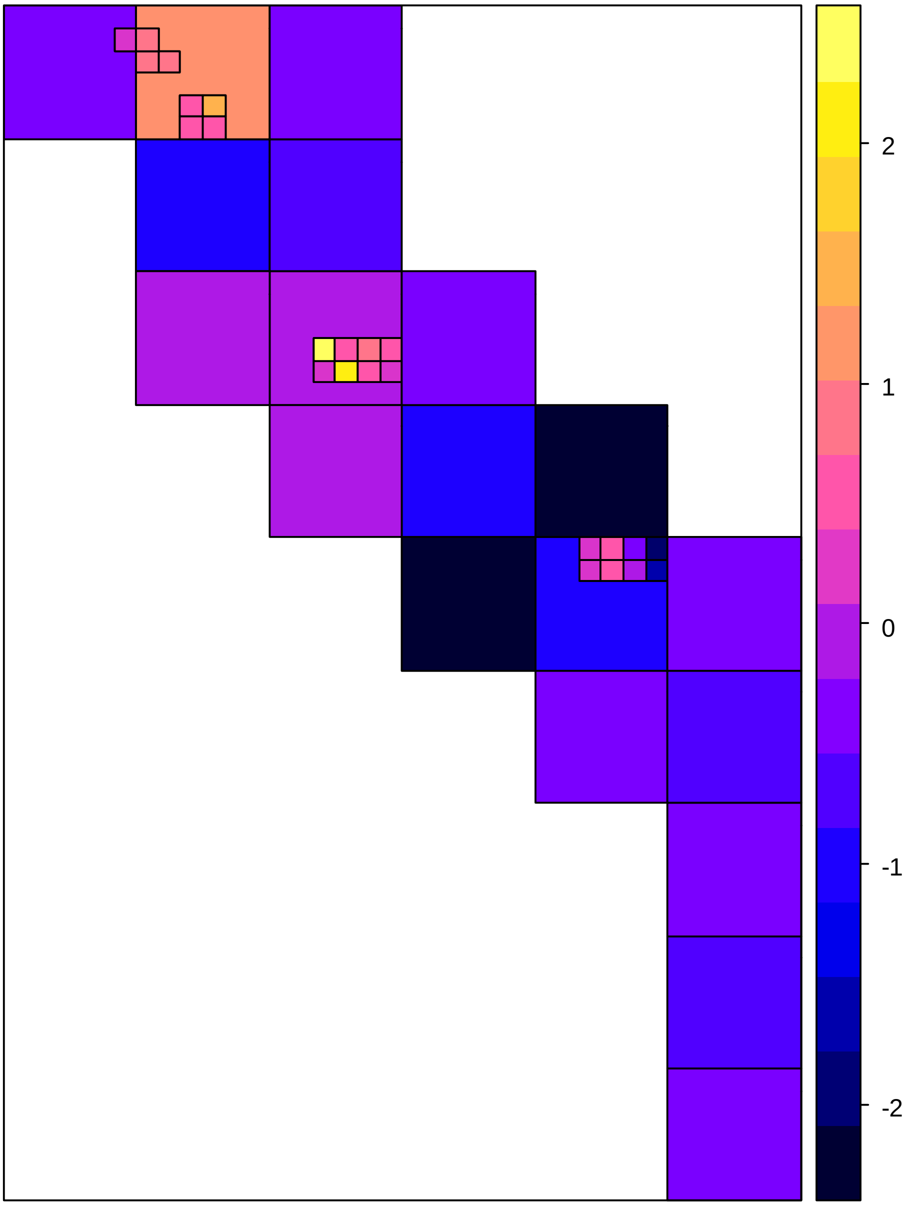

Figure 26 Posterior mode of the spatial random effect parameters, ψ_k , for model four.

16.4 MCMC output

16.4.1 Model One

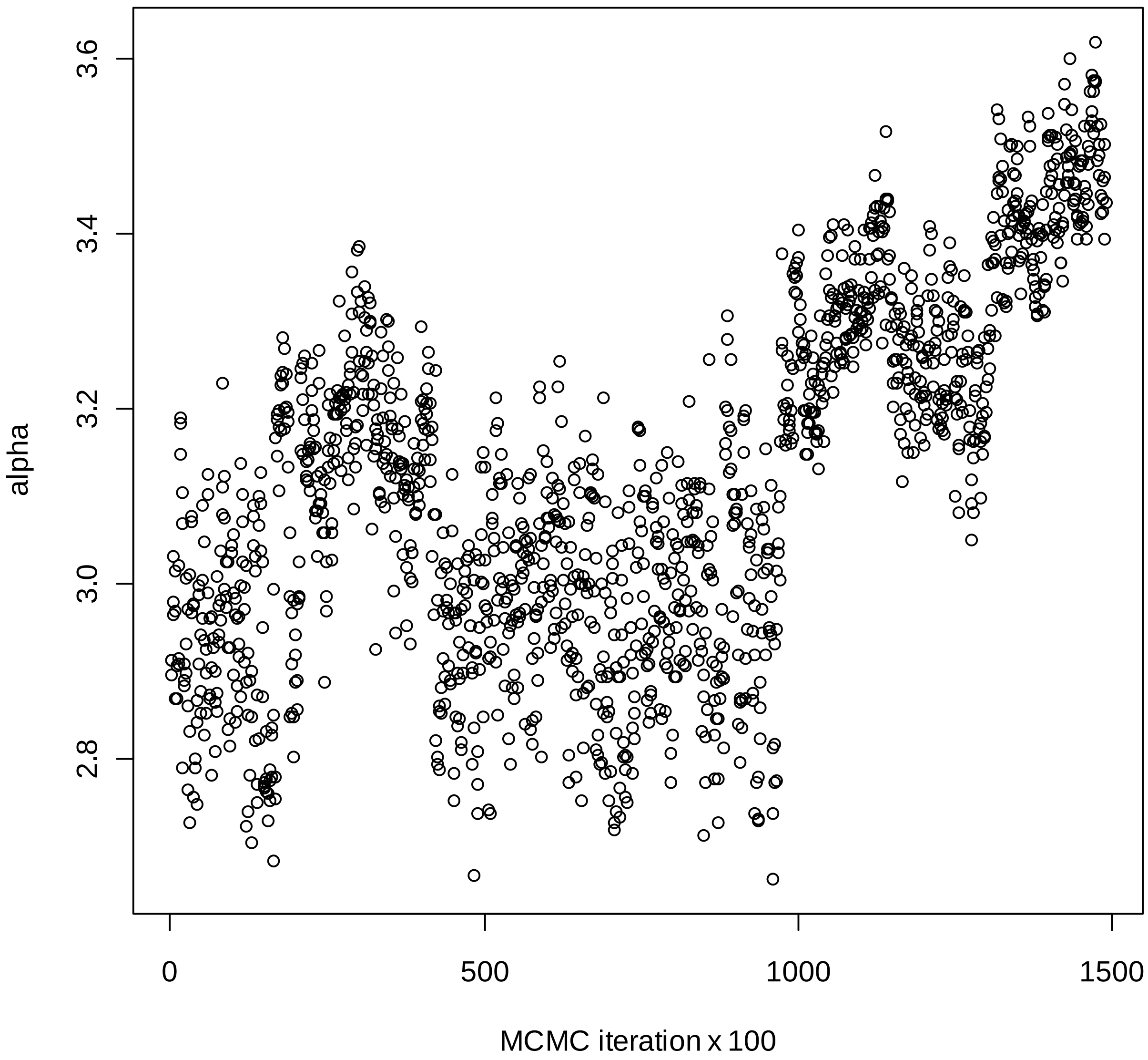

Figure 27 Markov chain Monte Carlo output over iterations for the α stock-recruitment parameter.

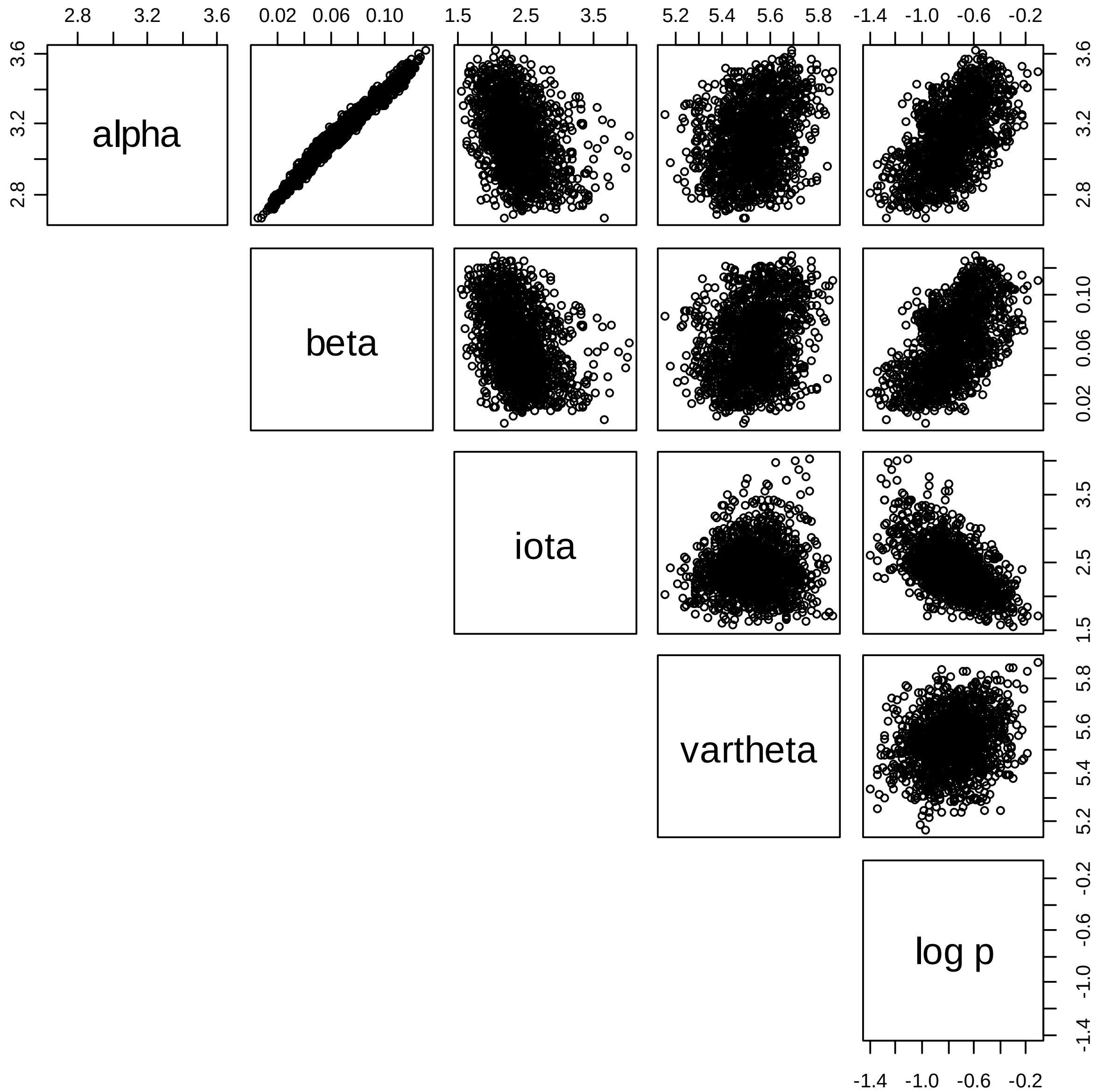

Figure 28 Markov chain Monte Carlo posterior pairwise correlation for five key parameters.

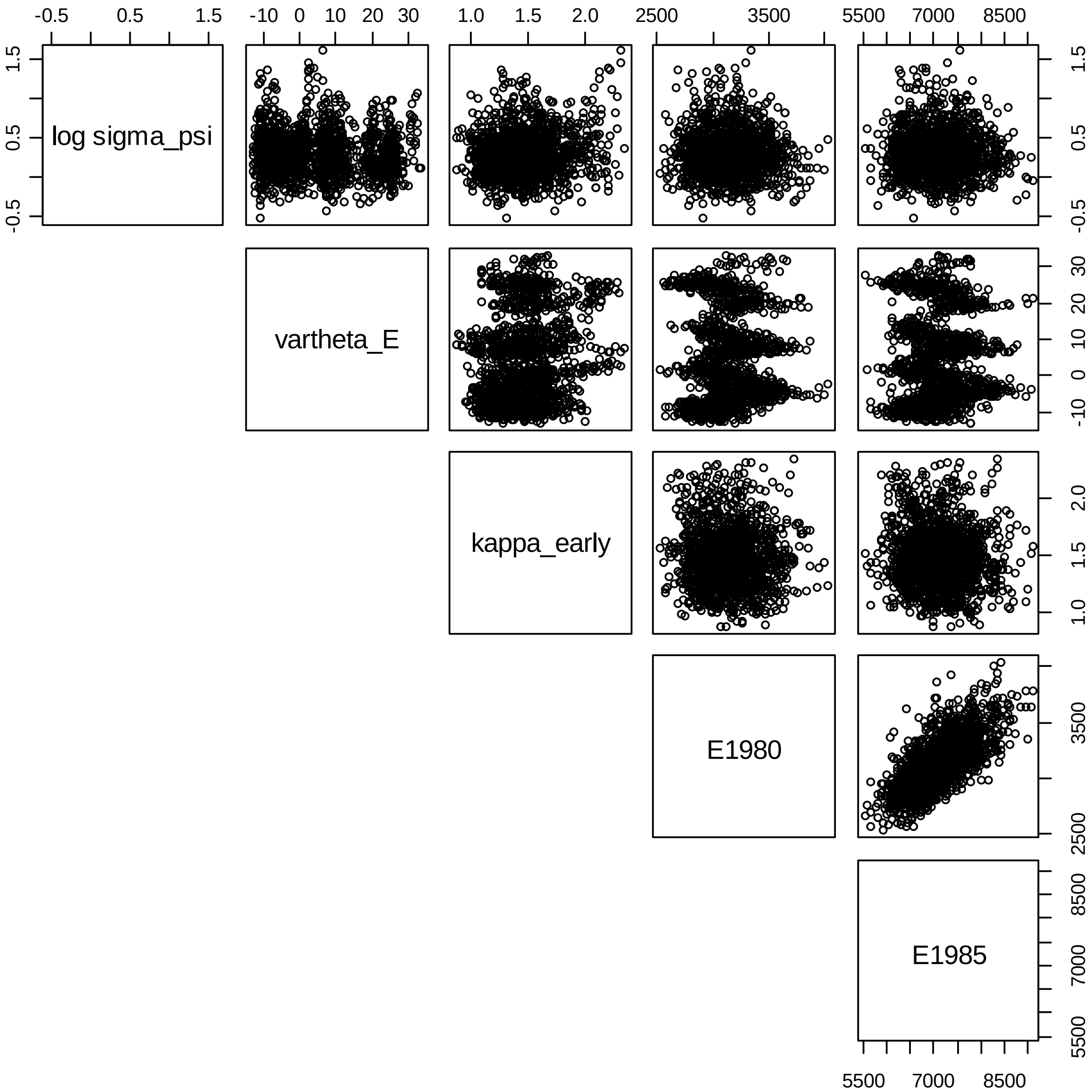

Figure 29 Markov chain Monte Carlo posterior pairwise correlation for five more parameters.

16.4.2 Model two

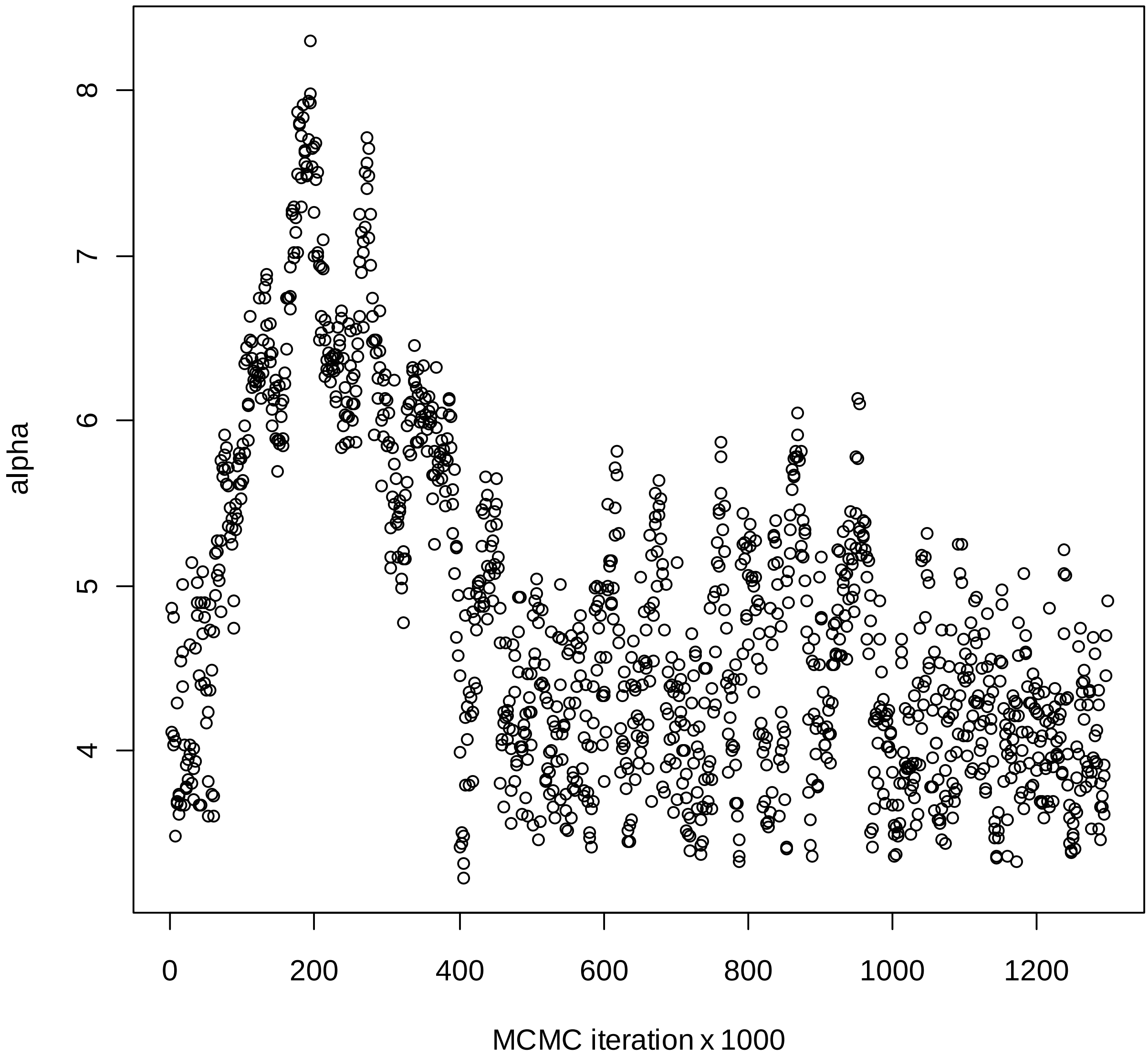

Figure 30 Markov chain Monte Carlo output for the α stock-recruitment parameter.

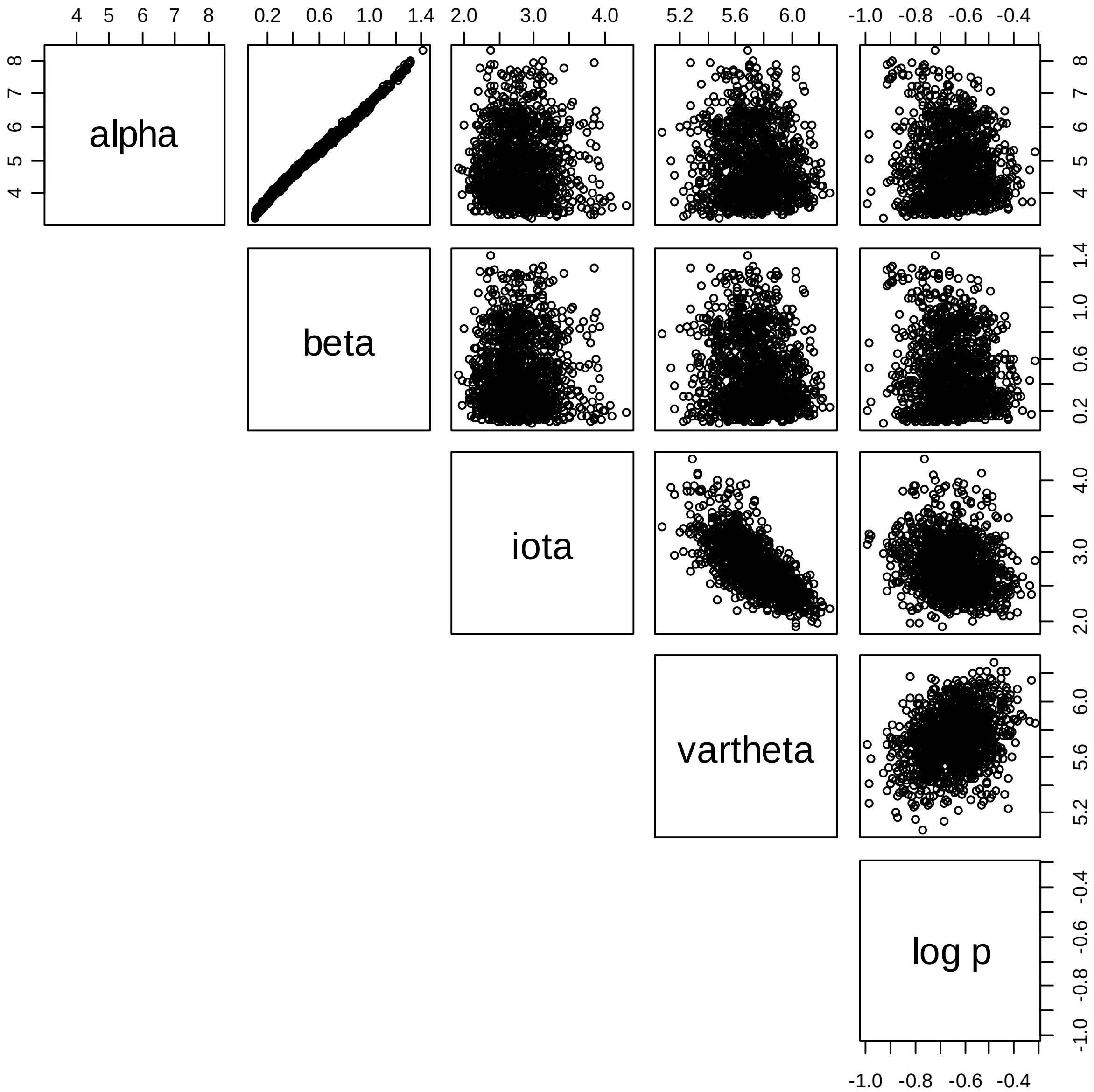

Figure 31 Markov chain Monte Carlo posterior pairwise correlation for five key parameters.

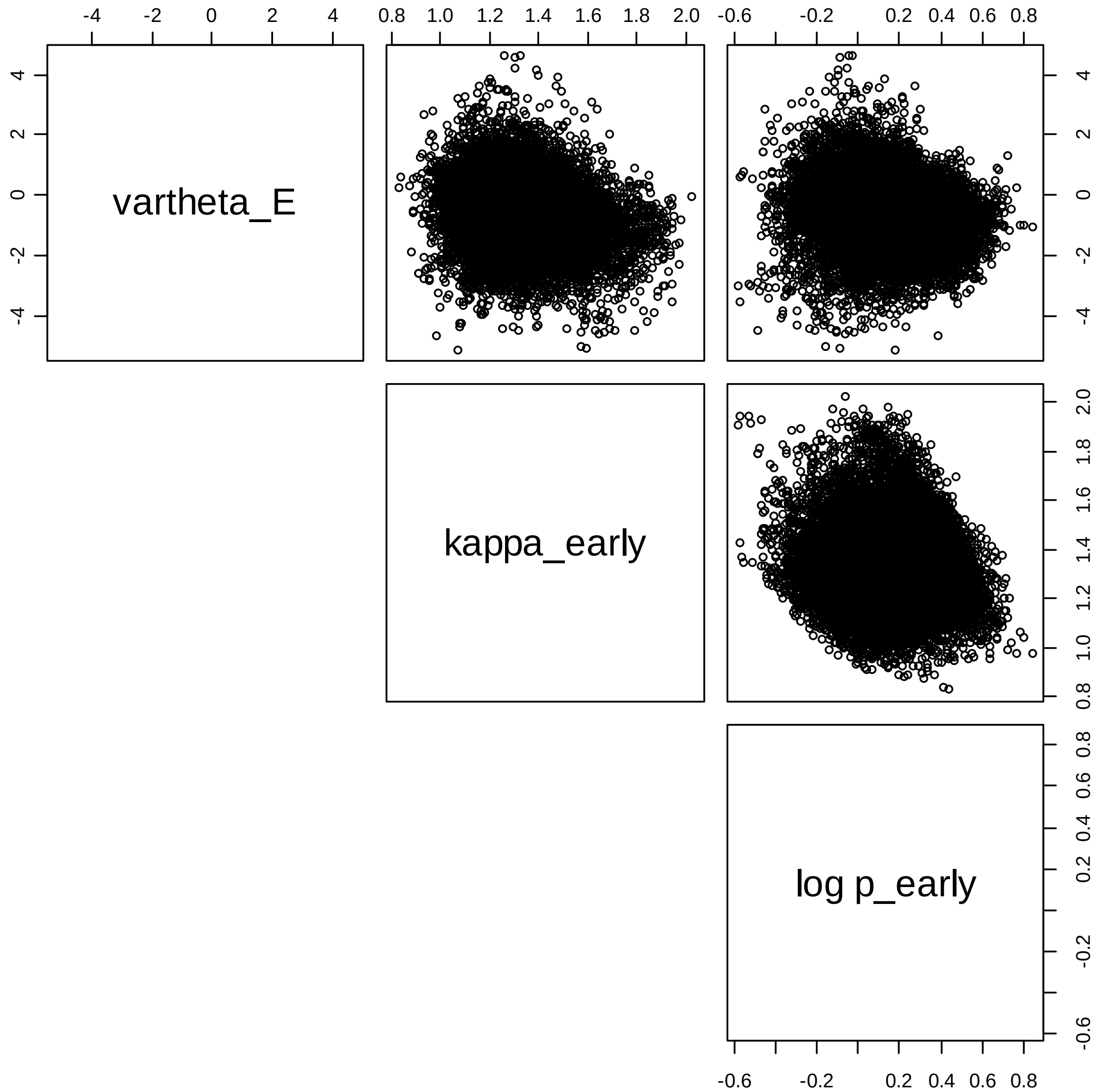

Figure 32 Markov chain Monte Carlo posterior pairwise correlation for three more parameters.

16.4.3 Model three

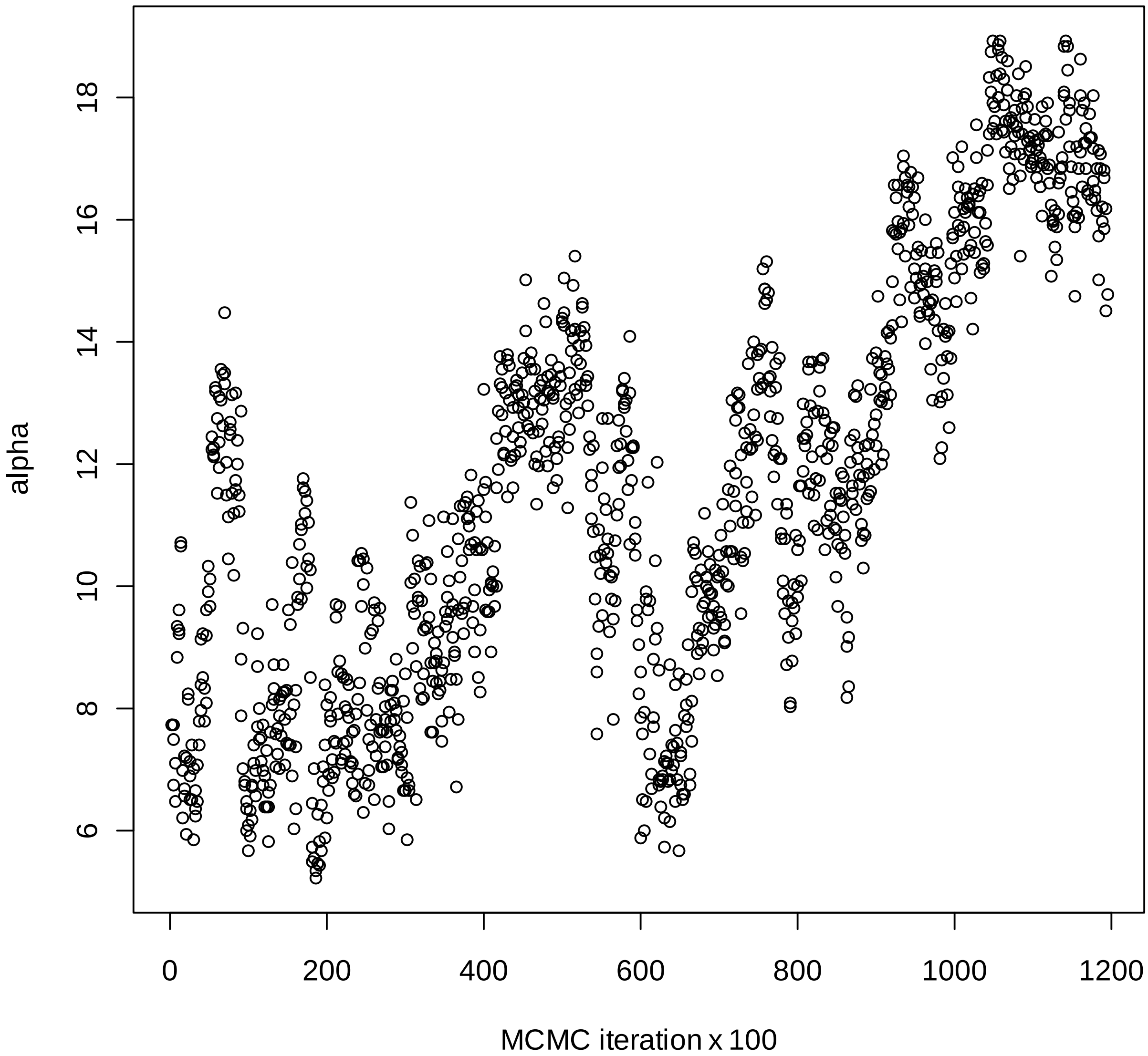

Figure 33 Markov chain Monte Carlo output for the α stock-recruitment parameter.

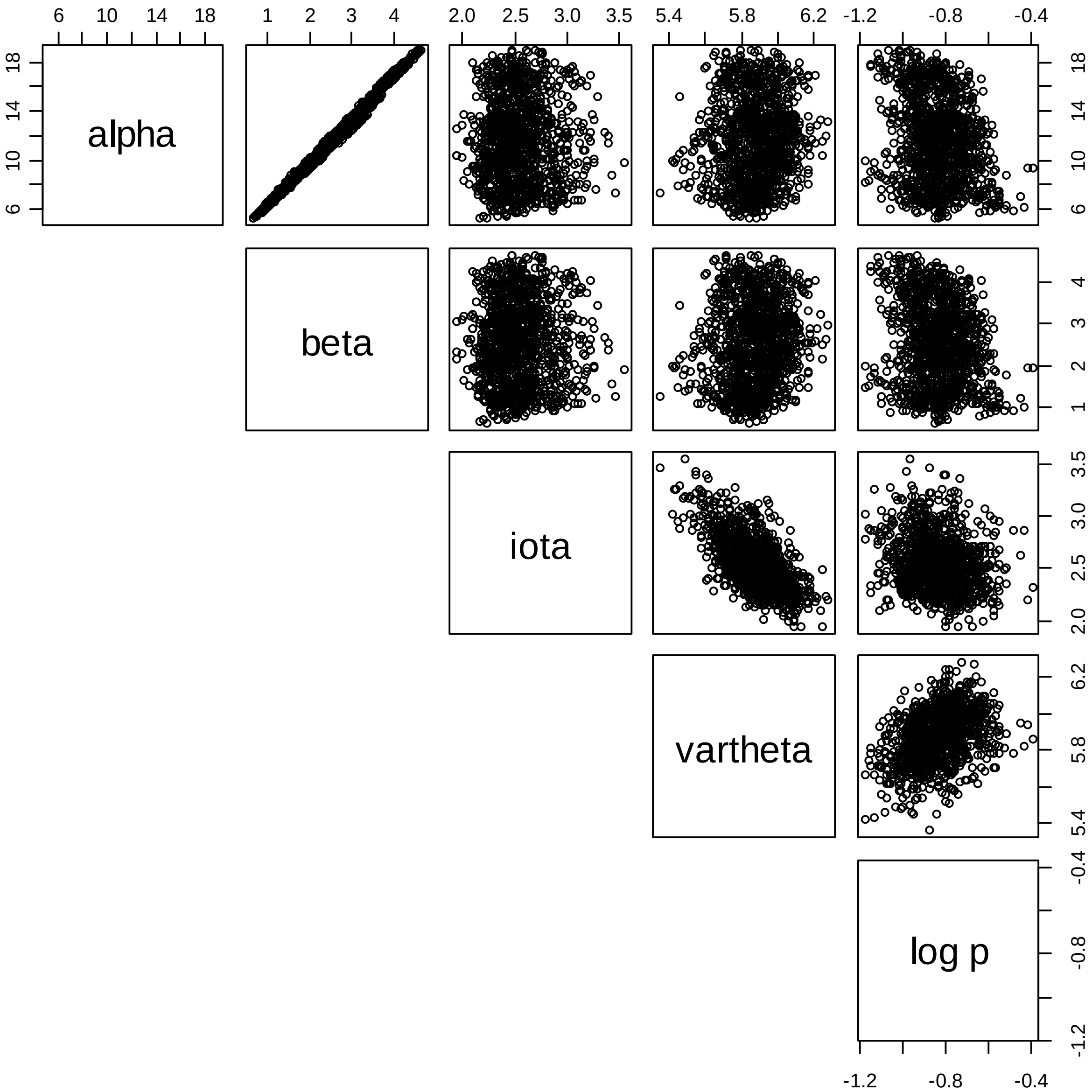

Figure 34 Markov chain Monte Carlo posterior pairwise correlation for five key parameters.

16.4.4 Model four

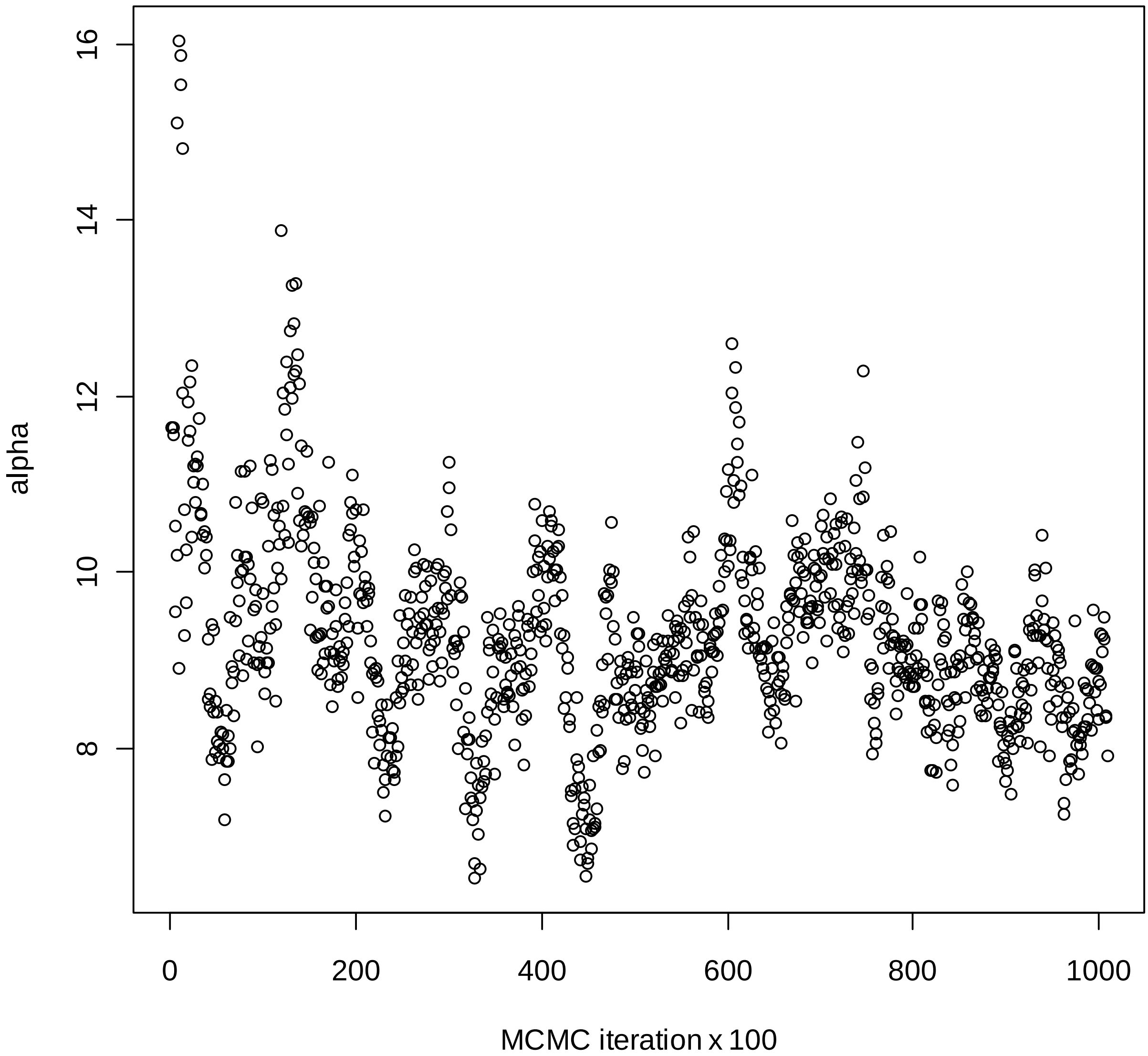

Figure 35 Markov chain Monte Carlo output for the α stock-recruitment parameter.

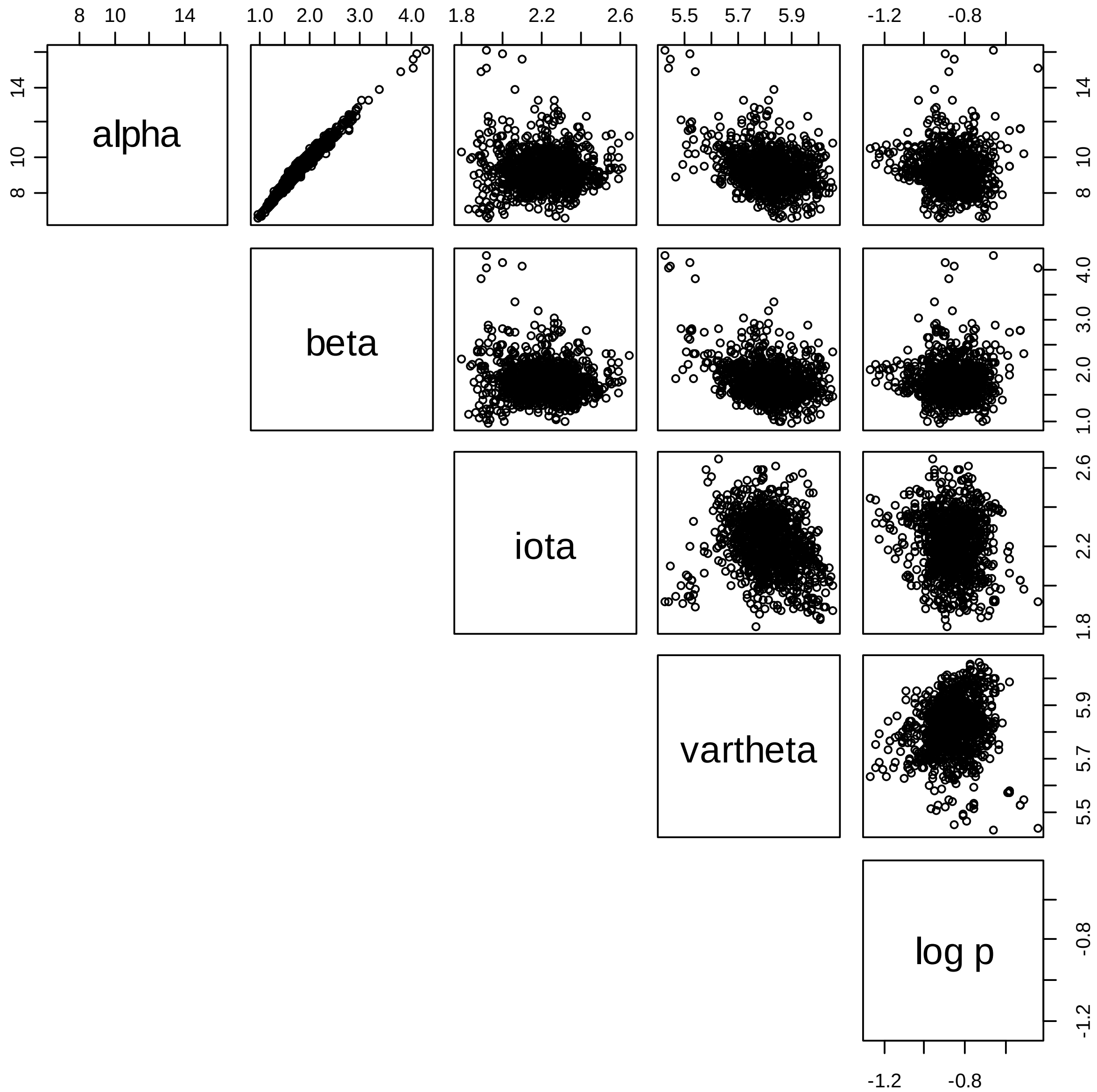

Figure 36 Markov chain Monte Carlo posterior pairwise correlation for five key parameters.

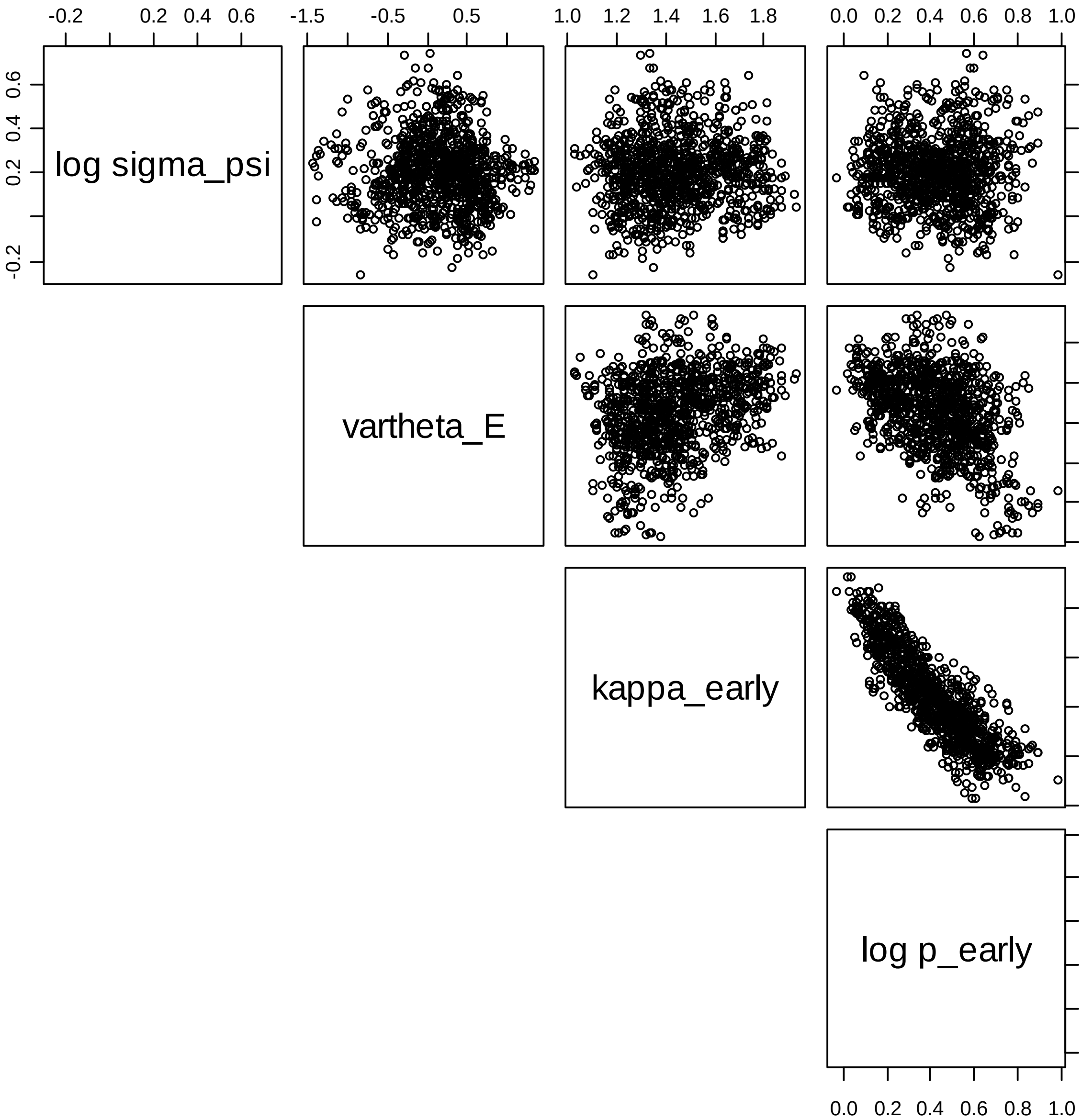

Figure 37 Markov chain Monte Carlo posterior pairwise correlation for four more parameters.

17 Appendix 5: Mathematics

17.1 Deriving the integrated catchability

Suspending strict adherence to previously defined notation, and treating N for the moment as measured in the same units as C, the Baranov catch equation is

$$\frac{C}{N} = \frac{F}{Z}(1 - e^{-Z})$$

which we can Taylor-series expand ($e^{-x} \approx 1 - x + x^2 / 2$) to give

$$\frac{C}{N} \approx \frac{F}{Z}\left(Z - \frac{Z^2}{2}\right)$$

$$= F\left(1 - \frac{Z}{2}\right)$$

$$= F - \frac{F^2}{2} - \frac{FM}{2}\,.$$

This formulation provides the equation

$$F^2 + (M-2)F + 2\frac{C}{N} = 0\,,$$

which can be solved for F as

$$F = \frac{-(M-2) + \sqrt{(M-2)^2 - 8\frac{C}{N}}}{2}.$$

Finally,

$$\overline{q} = \frac{F}{E}\,,$$

so, returning to defined notation, we can calculate $\overline{q}_i$ by substituting $E = f_y E_{i,*}$, $C = C_{i,*}$ and

$$N = \sum_j w_j S_{i,j} N_{i,j,*}$$