



# CASAL2 User Manual

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## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Necessary files . . . . .	1
1.2	Getting help . . . . .	1
1.3	Technical details . . . . .	1
<b>2</b>	<b>Model overview</b>	<b>3</b>
2.1	Introduction . . . . .	3
2.2	The population section . . . . .	4
2.3	The estimation section . . . . .	4
2.4	The observation section . . . . .	5
2.5	The report section . . . . .	5
<b>3</b>	<b>Running CASAL2</b>	<b>7</b>
3.1	Using CASAL2 . . . . .	7
3.2	The input configuration file . . . . .	7
3.3	Redirecting standard output . . . . .	8
3.4	Command line arguments . . . . .	8
3.5	Constructing a CASAL2 input configuration files . . . . .	9
3.5.1	Commands . . . . .	9
3.5.2	Subcommands . . . . .	10
3.5.3	The command-block format . . . . .	10
3.5.4	Commenting out lines . . . . .	11
3.5.5	Determining parameter names . . . . .	11
3.6	CASAL2 exit status values . . . . .	12
<b>4</b>	<b>The population section</b>	<b>13</b>
4.1	Introduction . . . . .	13
4.2	Population structure . . . . .	13
4.3	The state object and the partition . . . . .	15
4.4	Time sequences . . . . .	16
4.4.1	Initialisation . . . . .	17
4.5	Model run years . . . . .	18
4.6	Projection years . . . . .	19
4.7	Population processes . . . . .	19
4.7.1	Recruitment . . . . .	20
4.7.2	Ageing . . . . .	22
4.7.3	Mortality . . . . .	22
4.7.3.1	Constant mortality rate . . . . .	22
4.7.3.2	Event and biomass-event mortality . . . . .	23
4.7.3.3	Instantaneous mortality . . . . .	24
4.7.3.4	Hollings Rate . . . . .	25

4.7.4	Transition By Category . . . . .	26
4.7.4.1	Annual transition by category . . . . .	26
4.7.5	Tag Release events . . . . .	27
4.7.6	Tag Loss . . . . .	27
4.8	Derived quantities . . . . .	27
4.9	Age-length relationship . . . . .	28
4.10	Weightless model . . . . .	30
4.11	Maturity, in models without maturing in the partition . . . . .	30
4.12	Selectivities . . . . .	30
4.12.1	Constant . . . . .	31
4.12.2	Knife-edge . . . . .	31
4.12.3	All-values . . . . .	31
4.12.4	All-values-bounded . . . . .	31
4.12.5	Increasing . . . . .	31
4.12.6	Logistic . . . . .	32
4.12.7	Inverse logistic . . . . .	32
4.12.8	Logistic producing . . . . .	32
4.12.9	Double-normal . . . . .	32
4.12.10	Double-exponential . . . . .	32
4.12.11	Spline . . . . .	33
4.13	Time Varying Parameters . . . . .	33
4.13.1	Constant . . . . .	33
4.13.2	Random Walk . . . . .	33
4.13.3	Annual shift . . . . .	34
4.13.4	Exogenous . . . . .	34
<b>5</b>	<b>The estimation section</b>	<b>35</b>
5.1	Role of the estimation section . . . . .	35
5.2	The objective function . . . . .	35
5.3	Specifying the parameters to be estimated . . . . .	35
5.4	Point estimation . . . . .	36
5.4.1	The numerical differences minimiser . . . . .	36
5.4.2	The differential evolution minimiser . . . . .	37
5.4.3	Betadiff minimiser . . . . .	38
5.4.4	ADOL-C minimiser . . . . .	38
5.4.5	CPPAD minimiser . . . . .	38
5.4.6	Dlib minimiser . . . . .	38
5.5	Posterior profiles . . . . .	38
5.6	Bayesian estimation . . . . .	39
5.7	Priors . . . . .	42
5.8	Penalties . . . . .	43
5.9	Additional Priors . . . . .	44

<b>6</b>	<b>The observation section</b>	<b>45</b>
6.1	Observations and likelihoods . . . . .	45
6.2	Proportions-at-age observations . . . . .	45
6.2.1	Likelihoods for proportions-at-age observations . . . . .	48
6.3	Proportions-by-category observations . . . . .	49
6.3.1	Likelihoods for proportions-by-category observations . . . . .	50
6.4	Abundance or biomass observations . . . . .	51
6.4.1	Likelihoods for abundance observations . . . . .	52
6.5	Process error . . . . .	53
6.6	Ageing error . . . . .	53
6.7	Simulating observations . . . . .	54
6.8	Pseudo-observations . . . . .	55
<b>7</b>	<b>The report section</b>	<b>57</b>
7.1	Print the partition at the end of an initialisation . . . . .	57
7.2	Print the partition . . . . .	57
7.3	Print the age length and length weight values . . . . .	58
7.4	Print a process summary . . . . .	58
7.5	Print derived quantities . . . . .	58
7.6	Print the estimated parameters . . . . .	58
7.7	Print the estimated parameters in a vector format . . . . .	58
7.8	Print the objective function . . . . .	58
7.9	Print the covariance matrix . . . . .	58
7.10	Print observations, fits, and residuals . . . . .	58
7.11	Print simulated observations . . . . .	59
7.12	Print the ageing error misclassification matrix . . . . .	59
7.13	Print selectivities . . . . .	59
7.14	Print the random number seed . . . . .	59
7.15	Print the results of an MCMC . . . . .	59
7.16	Print the MCMC samples as they are calculated . . . . .	59
7.17	Print the MCMC objective function values as they are calculated . . . . .	59
7.18	Print time varying parameters . . . . .	60
7.19	Tabular reporting . . . . .	60
<b>8</b>	<b>Population command and subcommand syntax</b>	<b>61</b>
8.1	Model structure . . . . .	61
8.2	Initialisation . . . . .	62
8.2.1	Cinitial . . . . .	62
8.2.2	Derived . . . . .	62
8.2.3	Iterative . . . . .	63
8.2.4	State Category By Age . . . . .	63
8.3	Categories . . . . .	64

8.4	Time-steps . . . . .	64
8.5	Processes . . . . .	64
8.5.1	Ageing . . . . .	65
8.5.2	Growth . . . . .	65
8.5.3	Maturation . . . . .	65
8.5.4	Mortality Constant Rate . . . . .	66
8.5.5	Mortality Event . . . . .	66
8.5.6	Mortality Event Biomass . . . . .	67
8.5.7	Mortality Holling Rate . . . . .	68
8.5.8	Mortality Instantaneous . . . . .	69
8.5.9	Mortality Prey Suitability . . . . .	70
8.5.10	Nop . . . . .	71
8.5.11	Recruitment Beverton Holt . . . . .	71
8.5.12	Recruitment Constant . . . . .	72
8.5.13	Tag By Age . . . . .	73
8.5.14	Tag By Length . . . . .	74
8.5.15	Tag Loss . . . . .	75
8.5.16	Transition Category . . . . .	76
8.5.17	Transition Category By Age . . . . .	76
8.6	Time varying parameters . . . . .	77
8.6.1	Annual Shift . . . . .	77
8.6.2	Constant . . . . .	78
8.6.3	Exogenous . . . . .	78
8.6.4	Linear . . . . .	79
8.6.5	Random Walk . . . . .	79
8.7	Derived quantities . . . . .	80
8.7.1	Abundance . . . . .	80
8.7.2	Biomass . . . . .	81
8.8	Age-length relationship . . . . .	82
8.8.1	Data . . . . .	82
8.8.2	None . . . . .	83
8.8.3	Schnute . . . . .	84
8.8.4	Von Bertalanffy . . . . .	85
8.9	Length-weight . . . . .	86
8.9.1	Basic . . . . .	87
8.9.2	None . . . . .	87
8.10	Selectivities . . . . .	87
8.10.1	All Values . . . . .	88
8.10.2	All Values Bounded . . . . .	88
8.10.3	Constant . . . . .	88
8.10.4	Double Exponential . . . . .	89
8.10.5	Double Normal . . . . .	90



8.10.6	Increasing . . . . .	90
8.10.7	Inverse Logistic . . . . .	91
8.10.8	Knife Edge . . . . .	91
8.10.9	Logistic . . . . .	92
8.10.10	Logistic Producing . . . . .	92
<b>9</b>	<b>Estimation command and subcommand syntax</b>	<b>93</b>
9.1	Estimation methods . . . . .	93
9.1.1	Beta . . . . .	94
9.1.2	Lognormal . . . . .	95
9.1.3	Normal . . . . .	96
9.1.4	Normal By Stdev . . . . .	97
9.1.5	Normal Log . . . . .	98
9.1.6	Uniform . . . . .	99
9.1.7	Uniform Log . . . . .	99
9.2	Point estimation . . . . .	100
9.2.1	A D O L C . . . . .	100
9.2.2	Beta Diff . . . . .	101
9.2.3	C P P A D . . . . .	101
9.2.4	D E Solver . . . . .	102
9.2.5	D Lib . . . . .	102
9.2.6	Gamma Diff . . . . .	103
9.3	Monte Carlo Markov Chain (MCMC) . . . . .	103
9.3.1	Independence Metropolis . . . . .	104
9.4	Profiles . . . . .	105
9.5	Defining catchability constants . . . . .	106
9.5.1	Free . . . . .	106
9.6	Defining penalties . . . . .	106
9.6.1	Process . . . . .	106
9.7	Defining priors on parameter ratios, differences and means . . . . .	107
9.7.1	Beta . . . . .	107
9.7.2	Vector Average . . . . .	107
9.7.3	Vector Smoothing . . . . .	108
<b>10</b>	<b>Observation command and subcommand syntax</b>	<b>108</b>
10.1	Observation types . . . . .	108
10.1.1	Process Abundance . . . . .	109
10.1.2	Time Step Abundance . . . . .	111
10.1.3	Process Biomass . . . . .	112
10.1.4	Time Step Biomass . . . . .	113
10.1.5	Process Proportions At Age . . . . .	115
10.1.6	Time Step Proportions At Age . . . . .	116

10.1.7	Proportions At Age For Fishery . . . . .	118
10.1.8	Process Proportions At Length . . . . .	119
10.1.9	Time Step Proportions At Length . . . . .	121
10.1.10	Proportions At Length For Fishery . . . . .	122
10.1.11	Process Proportions By Category . . . . .	123
10.1.12	Time Step Proportions By Category . . . . .	125
10.1.13	Proportions Migrating . . . . .	126
10.1.14	Tag Recapture By Age . . . . .	128
10.1.15	Tag Recapture By Length . . . . .	129
10.2	Likelihoods . . . . .	131
10.2.1	Binomial . . . . .	132
10.2.2	Binomial Approx . . . . .	132
10.2.3	Dirichlet . . . . .	132
10.2.4	Log Normal . . . . .	132
10.2.5	Log Normal With Q . . . . .	132
10.2.6	Multinomial . . . . .	132
10.2.7	Normal . . . . .	132
10.2.8	Pseudo . . . . .	132
10.3	Defining ageing error . . . . .	132
10.3.1	Data . . . . .	132
10.3.2	Normal . . . . .	132
10.3.3	Off By One . . . . .	133
<b>11</b>	<b>Report command and subcommand syntax</b>	<b>133</b>
11.1	Report commands and subcommands . . . . .	133
11.1.1	Ageing Error Matrix . . . . .	134
11.1.2	Category Info . . . . .	134
11.1.3	Category List . . . . .	134
11.1.4	Correlation Matrix . . . . .	134
11.1.5	Covariance Matrix . . . . .	135
11.1.6	Derived Quantity . . . . .	135
11.1.7	Estimable . . . . .	135
11.1.8	Estimate Summary . . . . .	136
11.1.9	Estimate Value . . . . .	136
11.1.10	Hessian Matrix . . . . .	136
11.1.11	Initialisation Partition . . . . .	137
11.1.12	M C M C Covariance . . . . .	137
11.1.13	M C M C Objective . . . . .	137
11.1.14	M C M C Sample . . . . .	137
11.1.15	M P D . . . . .	138
11.1.16	Objective Function . . . . .	138
11.1.17	Observation . . . . .	138

11.1.18 Output Parameters . . . . .	139
11.1.19 Partition . . . . .	139
11.1.20 Partition Biomass . . . . .	139
11.1.21 Partition Mean Weight . . . . .	140
11.1.22 Process . . . . .	140
11.1.23 Random Number Seed . . . . .	141
11.1.24 Selectivity . . . . .	141
11.1.25 Simulated Observation . . . . .	141
11.1.26 Standard Header . . . . .	142
11.1.27 Time Varying . . . . .	142
<b>12 Other commands and subcommands</b>	<b>142</b>
<b>13 Examples</b>	<b>143</b>
13.1 An example of a simple model . . . . .	143
<b>14 Post processing output using R</b>	<b>145</b>
<b>15 Troubleshooting</b>	<b>147</b>
15.1 Introduction . . . . .	147
15.2 Reporting errors . . . . .	147
15.3 Guidelines for reporting a problem with CASAL2 . . . . .	147
<b>16 The Shorthand syntax section</b>	<b>149</b>
16.1 Categories . . . . .	149
16.2 Parameters . . . . .	150
16.3 In line declaration . . . . .	151
<b>17 The Developmental section</b>	<b>153</b>
17.0.1 Single stepping CASAL2 . . . . .	153
17.0.2 Estimate Transformations . . . . .	153
17.0.2.1 log . . . . .	153
17.0.2.2 Inverse . . . . .	154
17.0.2.3 Log odds . . . . .	154
17.0.2.4 Simplex . . . . .	154
<b>18 Acknowledgements</b>	<b>155</b>
<b>19 Quick reference</b>	<b>157</b>
<b>20 References</b>	<b>181</b>
<b>21 CASAL2 software license</b>	<b>183</b>
<b>22 Index</b>	<b>187</b>



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## 1. Introduction

CASAL2 is a generalised age-structured population dynamics modelling software package that allows flexibility in specifying model structure, population dynamics, parameter estimation, and model outputs. CASAL2 can model population dynamics for an age-structured population using a range of population dynamics observations, including mark-recapture, relative and absolute abundance time series, and age frequency data. CASAL2 does this by implementing an age-structured population dynamics model that can have user defined categories (e.g., immature, mature, male, female, predator, prey, etc.) to specify the population structure, and a user-defined age range. bsectionSystem requirements CASAL2 is available for most IBM compatible machines running 64-bit Linux and Microsoft Windows operating systems.

Several of CASAL2s tasks are highly computer intensive and a fast processor is recommended. Depending on the model implemented, some of CASAL2s tasks can take a considerable amount of time (minutes to hours), and in extreme cases can even take several days to undertake an MCMC estimate.

The program itself requires only a few megabytes of hard-disk space but output files can consume large amounts of disk space. Depending on number and type of user output requests, the output could range from a few hundred kilobytes to several hundred megabytes. When estimating model fits, several hundred megabytes of RAM may be required, depending on the spatial size of the model, number of categories, and complexity of processes and observations. For extremely large models, several gigabytes of RAM may occasionally be required.

### 1.1. Necessary files

For both 64-bit Linux and Microsoft Windows, only the binary file `casal2` or `casal2.exe` is required to run CASAL2. No other software is required. We do not compile a version for 32-bit operating systems.

CASAL2 offers little in the way of post-processing of model output, and a package available that allows tabulation and graphing of model outputs is recommended. We suggest software such as **R** (R Core Team, 2014) to assist in the post processing of CASAL2 output. We provide the CASAL2 **R** package for importing the CASAL2 output into **R** (see Section 14).

### 1.2. Getting help

CASAL2 is distributed as unsupported software, however we would appreciate being notified of any problems or errors in CASAL2. See Section 15.2 for the recommended template for reporting issues. For further information on CASAL2 please contact the development team at [casal@niwa.co.nz](mailto:casal@niwa.co.nz).

### 1.3. Technical details

CASAL2 was compiled on Linux using `gcc`, the C/C++ compiler developed by the GNU Project. The 64-bit Linux version was compiled using `gcc` version 5.2.1 20151010 (Ubuntu Linux). The Microsoft Windows version was compiled using Mingw32 `gcc` (tdm64-1) 5.1.0. The Microsoft Windows installer was built using the Inno Setup 5 application.

CASAL2 includes six different minimisers — Different minimisers may be better at some models than others. The first three are non-differentiation based minimisers: the first is closely based on the main algorithm of Dennis Jr and Schnabel (1996), and which which uses finite difference gradients;

the second is an implementation of the differential evolution solver (Storn and Price, 1995), and based on code by Lester E. Godwin of PushCorp, Inc.; and the third is Dlib (King, 2009). The three differentiation based minimisers are: ADOLC, an auto differentiation minimiser (Walther et al., 1996); CPPAD is an auto differentiation minimiser similar to ADOLC (Wächter and Biegler, 2006); and the third is a modified version of an older version of ADOL-C (v1.8.4) that was used in the original version of CASAL (Bull et al., 2012).

The random number generator used by CASAL2 uses an implementation of the Mersenne twister random number generator (Matsumoto and Nishimura, 1998). This, the command line functionality, matrix operations, and a number of other functions use the BOOST C++ library (Version 1.58.0).

Note that the output from CASAL2 may differ slightly on the different platforms due to different precision arithmetic or other platform dependent implementation issues. The source code for CASAL2 is available in the windows bundle or on the github repository at <https://github.com/NIWAFisheriesModelling/CASAL2>.

Unit tests of the underlying CASAL2 code are carried out at build time, using the GOOGLE mock and unit testing framework. The unit test framework aims to cover a significant proportion of the key functionality within the CASAL2 code base. The unit test code for CASAL2 is available as a part of the underlying source code.

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## 2. Model overview

### 2.1. Introduction

CASAL2 is an age-structured population dynamics model. It implements a statistical catch-at-age population dynamics, using a discrete time-step state-space model that represents a cohort-based population age structure .

CASAL2 is run from the console window on Microsoft Windows or from a terminal window on Linux. CASAL2 gets its information from input data files, the main one of which is the *input configuration file*. Commands and subcommands in the input configuration file are used to define the model structure, provide observations, define parameters, and define the outputs (reports) for CASAL2. Command line switches tell CASAL2 the run mode and where to direct its output. See Section 3 for details.

We define the model in terms of the *state*. The state consists of two parts, the *partition*, and any *derived quantities*. The state will typically change in each *time-step* of every year, depending on the *processes* defined for those time-steps in the model.

The *partition* is a representation of the population at an instance in time, and can be considered a matrix of the numbers of individuals within each category and at each age.

A *derived quantity* is a summary of the abundance or biomass in a selected part of the partition at some instance in time. Unlike the partition (which is updated as each new process is applied), a derived quantity records a single value for each year of the model run. Hence, derived quantities build up a vector of values over the time period represented by the model. For example, the total biomass of individuals in categories labelled, say, ‘mature’ at some instance in the annual cycle may be a derived quantity. The derived quantity is then available to the model to be reported, or to be an input into another process (for example, recruitment) at some instance in the model in a subsequent year.

The state at some instance in time is the term for the combination of the partition and any derived quantities at that instance in time. Throughout the model, changes to the state occur from the application of *processes*. This state then provides the basis for the generation of expected values for *observations*, as well as for reports and other outputs.

Running of the model consists of two steps — first the model state is initialised for a number of iterations (years), then the model runs over a range of predefined years.

Initialisation can be in one or more phases, and for each phase, the processes that occur in each year, and the order in which they are applied, need to be defined. The processes that occur is controlled by the *annual cycle*. This defines what processes happen in each model year and in what sequence. Further, the processes in each year are split up into one or more time-steps (with at least one process occurring in each time-step). You can think of each time-step as representing a particular part of the calendar year, or you can just treat them as an abstract sequence of events.

The division of the year into an arbitrary number of time-steps allows the user to specify the exact order in which processes occur, and how/when observations are evaluated. The user specifies the time-steps, their order, and the processes within each time-step. If more than one process occurs in the same time-step, then they occur in the order that they are specified.

Observations are always linked to a time-step, and are evaluated by the model in time-step in which they occur. Hence, time-steps can be used to break processes into groups, and assist in defining the timing of the observations within the annual cycle. The manner in which observations are evaluated and how the expected values are calculated by the model is described later in Section 6.

The population structure of CASAL2 follows the usual population modelling conventions and is similar to those implemented in, for example, CASAL (Bull et al., 2012). The model records the numbers of individuals by category and age (e.g., numbers of males and females at age). In general, cohorts are added via a recruitment event, are aged annually, and are removed from the population via various forms of mortality. The population is assumed to be closed (i.e., no immigration or emigration from the modelled area)

A model is implemented in CASAL2 using an input configuration file, which provides a complete description of the model structure (i.e., population structure, initialisation, and the subsequent population processes), observations, estimation methods, and reports (outputs) requested. CASAL2 runs from a console window on Microsoft Windows or from a text terminal on Linux. A model can be either *run*, estimable parameters can be *estimated* or *profiled*, *MCMC* distributions calculated, and these estimates can be *projected* into the future or used by CASAL2 as parameters of an operating model to *simulate* observations.

A model in CASAL2 is specified by an input configuration file, and comprises of four main components. These are the population section that defines the model structure, population dynamics, etc.; the estimation section that defines the methods of estimation (minimisation methods or MCMC algorithms) and the model parameters to be estimated; the observation section that defines the observational data and associated likelihoods; and the report section that defines the printouts and reports from the model and where these are saved. The input configuration file completely describes a model implemented in CASAL2. See Sections 8, 9, 10, and 11 for details and specification of CASAL2s command and subcommand syntax within the input configuration file.

### 2.2. The population section

The population section (Section 4) defines the model of the population dynamics. It describes the model structure (i.e. the population structure), initialisation method and phases, run and projection years (model period), population processes (for example, recruitment, migration, and mortality), selectivities, and key population parameters.

### 2.3. The estimation section

The estimation section (Section 5) specifies the parameters to be estimated, estimation methods, penalties and priors. Estimation is based on an objective function (e.g., negative log posterior). Depending on the run mode, the estimation section is used to specify the methods for finding a point estimate (i.e., the set of parameter values that minimizes the objective function), doing profiles, or MCMC methods and options, etc.

Further, the estimation section specifies the parameters to be estimated within each model run and the estimation methods. The estimation section specifies the choice of estimation method, which model parameters are to be estimated, priors, starting values, and minimiser control values.

Penalties and priors act as constraints on the estimation. They can either encourage or discourage (depending on the specific implementation) parameter estimates that are ‘near’ some value, and hence influence the estimation process. For example, a penalty can be included in the objective function to discourage parameter estimates that lead to models where the recorded catch was unable to be fully taken.



## **2.4. The observation section**

Types of observations, their values, and the associated error structures are defined in the observation section (Section 6). Observations are data which allow us to make inferences about unknown parameters. The observation section specifies the observations, their errors, likelihoods, and when the observations occur. Examples include relative or absolute abundance indices, proportions-at-age frequencies, tag recapture observations, etc. Estimation uses the observations to find values for each of the estimated parameters so that each observation is ‘close’ (in some mathematical sense) to a corresponding expected value.

## **2.5. The report section**

The report section (Section ??) specifies the model outputs. It defines the quantities and model summaries to be output to external files or to the standard output. While CASAL2 will provide informational messages to the screen, CASAL2 will only produce model estimates, population states, and other data as requested by the report section. Note that if no reports are specified, then no output will be produced.



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### 3. Running CASAL2

CASAL2 is run from the console window (i.e., the command line) on Microsoft Windows or from a terminal window on Linux. CASAL2 gets its information from input data files, the key one of which is the input configuration file.

The input configuration file is compulsory and defines the model structure, processes, observations, parameters (both the fixed parameters and the parameters to be estimated), and the reports (outputs) requested. The following sections describe how to construct the CASAL2 configuration file. By convention, the name of the input configuration file ends with the suffix `.cs12`, however, any file name is acceptable. Note that the input configuration file can ‘include’ other files as a part of its syntax. Collectively, these are called the input configuration file.

Other input files can, in some circumstances, be supplied, depending on what is required. For example, a file can be supplied that defines the starting point for estimation, as points from which to simulate observations, or as points from which to run projections.

Simple command line arguments are used to determine the actions or *tasks* of CASAL2, i.e., to run a model with a set of parameter values, estimate parameter values (either point estimates or MCMC), project quantities into the future, simulate observations, etc.,. Hence, the *command line arguments* define the *task*. For example, `-r` is the *run*, `-e` is the *estimation*, and `-m` is the *MCMC* task. The *command line arguments* are described in Section 3.4.

#### 3.1. Using CASAL2

To use CASAL2, open a console (i.e. the command prompt) window (Microsoft Windows) or a terminal window (Linux). Navigate to a directory of your choice, where your input configuration files are located. Then type `casal2` with any arguments (see Section 3.4 for the the list of possible arguments). CASAL2 will print output to the screen and return you to the command prompt when it completes its task. Note that the CASAL2 executable (binary) and shared libraries (extension `.dll`) must be either in the directory where you run it or in your systems `PATH`. The CASAL2 installer should update your path on Windows in any case, but see your operating system documentation for help on identifying or modifying your `PATH`.

#### 3.2. The input configuration file

The input configuration file is made up of four broad sections; the description of the population structure and parameters (the population section), the estimation methods and variables (the estimation section), the observations and their associated likelihoods (the observation section), and the outputs and reports that CASAL2 will return (the report section). The input configuration file is made up of a number of commands (many with subcommands) which specify various options for each of these components.

The command and subcommand definitions in the input configuration file can be extensive (especially when you have a model that has many observations), and can result in a input configuration file that is long and difficult to navigate. To aid readability and flexibility, we can use the input configuration file command `!include file`. The command causes an external file, `file`, to be read and processed, exactly as if its contents had been inserted in the main input configuration file at that point. The file name must be a complete file name with extension, but can use either a relative or absolute path as part of its name. Note that included files can also contain `!include` commands. See Section 12 for more detail.

### 3.3. Redirecting standard output

CASAL2 uses the standard output stream `standard output` to display run-time information. The standard error stream is used by CASAL2 to output the program exit status and run-time errors. We suggest redirecting both the standard output and standard error into files. With the bash shell (on Linux systems), you can do this using the command structure,

```
(casal2 [arguments] > out) >& err &
```

It may be useful to redirect the standard input, especially if you're using CASAL2 inside a batch job software, i.e.

```
(casal2 [arguments] > out < /dev/null) >& err &
```

On Microsoft Windows systems, you can redirect to standard output using,

```
casal2 [arguments] > out
```

And, on some Microsoft Windows systems (e.g., Windows10), you can redirect to both standard output and standard error, using the syntax,

```
casal2 [arguments] > out 2> err
```

Note that CASAL2 outputs a few lines of header information to the output. The header consists of the program name and version, the arguments passed to CASAL2 from the command line, the date and time that the program was called (derived from the system time), the user name, and the machine name (including the operating system and the process identification number). These can be used to track outputs as well as identifying the version of CASAL2 used to run the model.

### 3.4. Command line arguments

The call to CASAL2 is of the following form:

```
casal2[-c config_file] [task] [options]
```

**-c *config\_file*** Define the input configuration file for CASAL2. If omitted, then CASAL2 looks for a file named `config.csl2`.

and where *task* is one of;

**-h** Display help (this page).

**-l** Display the reference for the software license (GPL v2).

**-v** Display the CASAL2 version number.

**-r** Run the model once using the parameter values in the input configuration file, or optionally, with the values from the file denoted with the command line argument `-i file`.

**-e** Do a point *estimate* using the values in the input configuration file as the starting point for the parameters to be estimated, or optionally, with the start values from the file denoted with the command line argument `-i file`.

- p** Do a likelihood *profile* using the parameter values in the input configuration file as the starting point, or optionally, with the start values from the file denoted with the command line argument `-i file`.
- m** Do an *MCMC* estimate using the values in the input configuration file as the starting point for the parameters to be estimated, or optionally, with the start values from the file denoted with the command line argument `-i file`.
- f** Project the model *forward* in time using the parameter values in the input configuration file as the starting point for the estimation, or optionally, with the start values from the file denoted with the command line argument `-i file`.
- s number** Simulate the *number* of observation sets using values in the input configuration file as the parameter values, or optionally, with the values for the parameters denoted as estimated from the file with the command line argument `-i file`.

In addition, the following are optional arguments [*options*],

- i file** Input one or more sets of free (estimated) parameter values from *file*. See Section 11 for details about the format of *file*.
- o file** Output a report of the free (estimated) parameter values in a format suitable for `-i file`. See Section 11 for details about the format of *file*.
- g seed** Seed the random number *generator* with *seed*, a positive (long) integer value. Note, if `-g` is not specified, then CASAL2 will generate a random number seed based on the computer clock time.
- loglevel** arg = {trace, finest, fine, medium} See Section ??.
- tabular** Run with `-r` or `-f` command it will print @report in tabular format. See Section ??.
- single-step** Run with `-r`, this additional option will pause the model and ask the user to specify parameters and their values to use for the next iteration. See Section 17.0.1.

### 3.5. Constructing a CASAL2 input configuration files

The model definition, parameters, observations, and reports are specified in an input configuration files. The population section is described in Section 4 and the population commands in Section 8. Similarly, the estimation section is described in Section 5 and its commands in Section 9, and in Section ?? and Section 11 for the report and report commands.

#### 3.5.1. Commands

CASAL2 has a range of commands that define the model structure, processes, observations, and how tasks are carried out. There are three types of commands,

1. Commands that have an argument and do not have subcommands (for example, `!include file`)
2. Commands that have a label and subcommands (for example @process must have a label, and has subcommands)
3. Commands that do not have either a label or argument, but have subcommands (for example @model)

Commands that have a label must have a unique label, i.e., the label cannot be used on more than one command of that type. The labels can contain alpha numeric characters, period ('.'), underscore ('\_') and dash ('-'). Labels must not contain white-space, or other characters that are not letters, numbers, dash, period or an underscore. For example,

```
@process NaturalMortality  
or  
!include MyModelSpecification.csl2
```

### 3.5.2. Subcommands

Subcommands in CASAL2 are for defining options and parameter values for commands. They always take an argument which is one of a specific *type*. The types acceptable for each subcommand are defined in Section 12, and are summarised below.

Like commands (@command), subcommands and their arguments are not order specific — except that that all subcommands of a given command must appear before the next @command block. CASAL2 may report an error if they are not supplied in this way, however, in some circumstances a different order may result in a valid, but unintended set of actions, leading to possible errors in your expected results.

The arguments for a subcommand are either:

<b>switch</b>	true/false
<b>integer</b>	an integer number,
<b>integer vector</b>	a vector of integer numbers,
<b>integer range</b>	a range of integer numbers separated by a colon (:), e.g. 1994:1996 is expanded to an integer vector of values 1994 1995 1996),
<b>constant</b>	a real number (i.e. double),
<b>constant vector</b>	a vector of real numbers (i.e. vector of doubles),
<b>estimable</b>	a real number that can be estimated (i.e. estimable double),
<b>estimable vector</b>	a vector of real numbers that can be estimated (i.e. vector of estimable doubles),
<b>string</b>	a categorical (string) value, or
<b>string vector</b>	a vector of categorical values.

Switches are parameters which are either true or false. Enter *true* as true or t, and *false* as false or f.

Integers must be entered as integers (i.e., if year is an integer then use 2008, not 2008.0)

Arguments of type integer vector, integer range, constant vector, estimable vector, or categorical vector contain one or more entries on a row, separated by white space (tabs or spaces).

*Estimable* parameters are those parameters that CASAL2 can estimate, if requested. If a particular parameter is not being estimated in a particular model run, then it acts as a constant. Within CASAL2 only estimable parameters can be estimated. And, you have to tell CASAL2 those that are to be estimated in any particular model. Estimable parameters that are being estimated within a particular model run are called the *estimated parameters*.

### 3.5.3. The command-block format

Each command-block either consists of a single command (starting with the symbol @) and, for most commands, a unique label or an argument. Each command is then followed by its subcommands

and their arguments, e.g.,

```
@command, or
@command argument, or
@command label
```

and then

```
subcommand argument
subcommand argument
etc.,
```

Blank lines are ignored, as is extra white space (i.e., tabs and spaces) between arguments. But don't put extra white space before a @ character (which must also be the first character on the line), and make sure the file ends with a carriage return.

There is no need to mark the end of a command block. This is automatically recognized by either the end of the file, section, or the start of the next command block (which is marked by the @ on the first character of a line). Note, however, that the *!include* is the only exception to this rule. See Section 12) for details of the use of *!include*.

Note that in the input configuration file, commands, sub-commands, and arguments are not case sensitive. However, labels and variable values are case sensitive. Also note that if you are on a Linux system then external calls to files are case sensitive (i.e., when using *!include file*, the argument *file* will be case sensitive).

#### 3.5.4. Commenting out lines

Text that follows a # on a line are considered to be comments and are ignored. If you want to remove a group of commands or subcommands using #, then comment out all lines in the block, not just the first line.

Alternatively, you can comment out an entire block or section by placing curly brackets around the text that you want to comment out. Put in a { as the first character on the line to start the comment block, then end it with }. All lines (including line breaks) between { and } inclusive are ignored.

```
# This is a comment and will be ignored
@process NaturalMortality
m 0.2
{
This block of code
is a comment and
will be ignored
}
```

#### 3.5.5. Determining parameter names

When CASAL2 processes a input configuration file, it translates each command and each subcommand into a parameter with a unique name. For commands, this parameter name is simply the command label. For subcommands, the parameter name format is either

```
command[label].subcommand if the command has a label, or
```

`command.subcommand` if the command has no label, or

`command[label].subcommand(i)` if the command has a label and the subcommand arguments are a vector, and we are accessing the  $i$ th element of that vector.

`command[label].subcommand(i:j)` if the command has a label, and the subcommand arguments are a vector, and we are accessing the elements from  $i$  to  $j$  (inclusive) of that vector.

The unique parameter name is used to reference the parameter when estimating, applying a penalty, projecting, time varying or applying a profile. For example, the parameter name of subcommand `m` of the command `@process` with the label `NaturalMortality` is

```
process[NaturalMortality].m
```

#### 3.6. CASAL2 exit status values

When CASAL2 completes its task successfully or errors out gracefully, it returns a single exit status value 'completed' to the standard output. Error messages will be printed to the console. If configuration errors are found, CASAL2 will print an error messages along with the associated files and line numbers where the errors were identified.



---

## 4. The population section

### 4.1. Introduction

The population section specifies the model structure, population dynamics, and other associated parameters. It describes the model structure (population structure), defines the population processes (e.g., recruitment, migration, and mortality), selectivities, and their parameters.

The population section consists of several components, including;

- The population structure;
- Model initialisation (i.e., the state of the partition at the start of the first year);
- The years over which the model runs (i.e., the start and end years of the model)
- The annual cycle (time-steps and processes that are applied in each time-step);
- The specifications and parameters of the population processes (i.e., processes that add, remove individuals to or from the partition, or shift numbers between ages and categories in the partition);
- Selectivities;
- Parameter values and their definitions;
- Derived quantities, required as parameters for some processes (e.g. Mature biomass to resolve any density dependent processes such as the spawner-recruit relationship, in a recruitment process).

### 4.2. Population structure

The basic structure of population section of a CASAL2 model is defined in terms of an annual cycle, time steps, states, and transitions.

The annual cycle defines what processes happen in each model year, and in what sequence. CASAL2 runs on an annual cycle rather than, for example, a 6-monthly cycle.)

Each year is split into one or more time steps, with at least one process occurring in each time step. Each time step can be thought of as representing a particular part of the calendar year, or you can just treat them as an abstract sequence of events. In every time step, there exists a mortality block, this is a group of consecutive mortality based processes, where individuals are removed from the partition. For more information on mortality blocks see Section 4.4 for more detail.

The state is the current status of the population, at any given time. The state can change one or more times in every time step of every year. The state object must contain sufficient information to figure out how the underlying population changes over time (given a model and a complete set of parameters).

There are a number of possible changes in the state, which are called transitions. These include processes that include recruitment, natural mortality, anthropogenic mortality, ageing, migration, tagging events, and maturation. Different processes may be useful for different models in different circumstances.

The division of the year into an arbitrary number of time steps allows the user to specify the exact order in which processes and observations occur throughout the year. The user needs to specify the time step in which each process occurs. If more than one process occurs in the same time step, they will be applied in the order specified in the `@time_step` block.

The key element of the state is the partition. This is a broadly applicable concept that can be used to describe many different kinds of population model. The partition is simply a breakdown of the total number of individuals in the current population into different categories. (Note that the partition records numbers of individuals, not biomass). The individuals are grouped into categories, for example, sex, maturity state, area, and species. However CASAL2 has no predefined categories, and these are defined by the user. This differs from CASAL (Bull et al., 2012) that has only pre-defined partition categories.

The resulting partition can be conceptualised as a matrix, where each row is represented by a category and the columns are the age classes, shown in Figure 4.1. Each row represents the number of individuals for that category in that age class.

The names of categories are user defined, and there must be at least one category defined for a model. The ages are defined as a sequence from  $age_{min}$  to  $age_{max}$ , with the last age optionally a plus group. In order to calculate biomass, the age-length relationship for each category must also be defined for an age based model (but could be defined as 'none'). An example of how this is specified for four categories based on sex and area is as follows,

```
@categories
format mature.sex
names spawn.male spawn.female nonspawn.male nonspawn.female
age_lengths male_AL female_AL male_AL female_AL
```

For an example of these ideas, consider a model of a fish population with a mature and non-spawning fishery. If we assume that the non-spawning fishery happens over most of the year (say 10 months) in the non-spawning area. The mature fish then migrate to the spawning area, where the spawning fishery operates. At the end of spawning, these fish, along with the recruits from the previous year, migrate back to the non-spawning area. The modeller decides that fish will be divided in the partition by age, sex, maturity, and area (spawning and non-spawning grounds). So the partition has 8 rows (2 sexes (mature or immature) 2 areas) and one column per age class.



**Figure 4.1: A visual representation of a partition**

So they define four time steps, labelled 1 through 4. Step 1 includes the non-spawning fishery. Step 2 includes the migration to the spawning area. Step 3 includes the spawning fishery. Step 4 includes recruitment and the migration back to the non-spawning area. (In fact, they could have used only 3 time steps, by using a single step in place of their steps 2 and 3. Because the default order of processes within a time step places migrations before fisheries, the processes would still have occurred in the right order.) There are other details to be sorted out, such as the proportion of natural mortality occurring in each time step and where observations occur, but this gives the basic idea.

This structure can be used to implement complex models, with intermingling of separate species and stocks, with complex migration patterns over multiple areas, and multiple sources of anthropogenic impact using different methods and covering different areas and times. However, we note that there is little point in using a complex structure to model a population when there are no observations to support that structure. In other words, use a structure for your model that is compatible with the data available. For information on how to define categories and using CASAL2's shorthand syntax see Section 16.

The model is run from an initial year up to the final(current) year. It can also be run past the final year to make projections — things that happen in the future — up to the final projection year.

An example, to specify a model with 2 categories (male and female) with ages 1-20 (with the last age a plus group) and an age-length relationship defined with the label `male_growth` and `female_growth`, then the `@model` example from above becomes,

```
@model
start_year
final_year
min_age 1
max_age 20
age_plus_group True
initialisation_phases iphase
time_steps step1 step2
```

### 4.3. The state object and the partition

The key component of the state object is the partition, a matrix that store numbers of individuals at age for each category. A category represents a group of individuals that have the same specific attributes, examples of such attributes include life histories and growth rates, etc. For example, categories may include labels such as:

- Sex (male or female);
- Area (any number of areas, named by the user);
- Maturity (immature or mature);
- Growth-path (any number of growth-paths);
- Tag (any number of tagging events);
- Species

A stock can be thought of as a population of individuals which recruits separately. See Section 4.11 for the treatment of maturity when it is not a category in the partition.

So, you need to tell CASAL2 the following:

- The minimum and maximum age classes in an age-based model.
- Whether there is an age-plus group.
- The names of all categories.

Age classes are always one year wide, except that the maximum age group can optionally be a plus group. Users need to choose the minimum and maximum age classes.

CASAL2 allows categories of the partition to exist for certain years of the model. This is added for computational efficiency, when models contain a large number of categories that do not persist

for all model years. Situations where this is beneficial is when a model contains a process that does a one off transition of fish from one category into another category in a subset of the model initialisation phases or years (for example, tagging events). Excluding categories for certain years can save a considerable amount of time as CASAL2 does not need to, for example, initialise empty categories or implement processes in time periods when they have no effect.

Another important component of the state object in CASAL2 are derived quantities. This includes quantities such as a mature biomass (for example, in fisheries models, the mid-spawning season biomasses of spawning fish, SSB) for either one or sum of more than one category. CASAL2 derives through the command `@derived_quantity`, and may be required in the specification of some processes (i.e., in fisheries models, a recruitment process that specifies a stock recruitment relationship requires the definition of a derived quantity that specifies the mid-season spawning stock biomass).

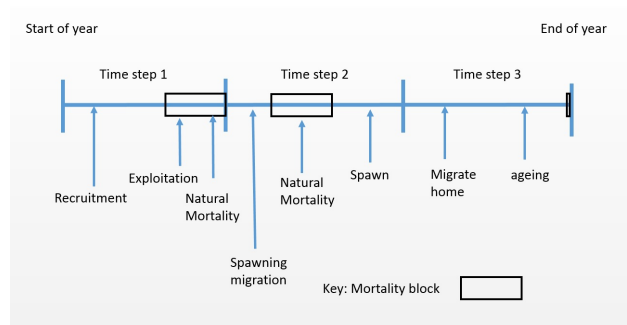
#### 4.4. Time sequences

The time sequence of the model is defined in the following parts;

- Annual cycle
- Initialisation
- Model run years
- Projection years

##### Annual cycle

The annual cycle is implemented as a set of processes that occur, in a user-defined order, within each year. Time-steps are used to break the annual cycle into separate components, and allow observations to be associated with different time periods and processes. Any number of processes can occur within each time-step, in any order (although there are limitations around mortality based processes - see Section 4.4) and can occur multiple times within each time-step. Note that time-steps are not implemented during the initialisation phases (effectively, there is only one time-step), and that the annual cycle in the initialisation phases can, optionally, be different from that which is applied during the model years.



**Figure 4.2:** A visual representation of a hypothetical sequence for an annual cycle.

## Mortality blocks

For every time step in an annual cycle there is an associated mortality block. As mentioned earlier a mortality block is a consecutive sequence of mortality processes. These include all the processes described under subsection 4.7.3. Each time step can have at most one mortality block, and if no mortality processes occur in a time step then it defaults to the end of the time step. CASAL2 will error out if the user defines multiple mortality processes in a single time step, that are not consecutive processes. Mortality blocks are related to derived quantities

Mortality blocks are an important concept in the model structure, and is used for derived quantities (see Section 4.8) and observations (see Section 6).

### 4.4.1. Initialisation

There are multiple methods to initialise a partition in CASAL2. These methods are: iterative, fixed, derived, and Cinitial. Model initialisation can occur in several phases, each of which can be a different method. At the end of the initialisation step, CASAL2 then runs through the model years carrying out processes in the order defined in the annual cycle, and can evaluate expected values of observations in order to calculate likelihoods, project the model forward to determine future states, or simulate observations from the current state.

#### Iterative Initialisation

One of CASAL2 methods for initialising the initial equilibrium state as an iterative process: a general solution that initialises complex structured models that may be difficult or impossible to implement using analytic approximations. However, initialising via iteration for a long-lived species with complex transitions can take many iterations and may be slow to run. In CASAL2, we allow for user-defined multi-phased initialisation to allow the user to phase the initialisation and assist with optimising the models for speed. Each phase of the initialisation can involve any number of processes. Note that the number of iterations in the initialisation may affect the model outputs, and that a period should be chosen to allow the population state to fully converge. CASAL2 can report convergence statistics to assist the user determine an appropriate method of initialisation.

In addition, each initialisation phase can optionally be stopped early if a user defined convergence criteria is met. For a set of user defined years in the initialisation phase, convergence is defined as met if the proportional absolute summed difference between the the state in year  $t - 1$  and the state in year  $t$  ( $\hat{\lambda}$ ) is less than a user defined  $\lambda$  where,

$$\hat{\lambda} = \frac{\sum_i \sum_j |\text{element}(i, j)_t - \text{element}(i, j)_{t-1}|}{\sum_i \sum_j \text{element}(i, j)_t} \quad (4.1)$$

In each initialisation phase, the processes defined for that phase are carried out and used as the starting point for the following phase or, if it is the last phase, then the years that the model is run over. The *first* phase is always initialised with each element (i.e., each age and category) set at zero. Note that this means that recruitment processes where the numbers of recruits is based on a stock recruitment or density dependant relationship will likely fail if used in the first phase of an initialisation.

The multi-phase iteration allows the user to determine if the initialisation has converged in a particular model run. Here, add an additional initialisation phase for, say, 1 year as the last

initialisation phase (with the same processes applied). Then, using the initialisation reports (`@report[label].type=initialisation_partition`), print a copy of the partition just before and just after that phase. If the initialisation has converged to an equilibrium state, then the partition at both these time intervals will be the same.

Hence, for an iterative initialisation you need to define;

- The initialisation phases.
- The number of years in each phase and the processes to apply in each (default is the annual cycle).

### Derived Initialisation

Derived initialisation is an analytical solution to calculate the equilibrium plus group using a geometric series. The benefit of this method is it can be solved in `max_age - min_age + 1` years, so is computationally faster than the iterative initialisation phase. Users should be warned that we have found under some process combinations (for example. one way migrations) that this solution does not reach the exact equilibrium partition. We advise to use this method for the computation benefits, but you should always compare to an iterative initialisation to satisfy the assumption that the partition is at an equilibrium state.

### Cinitial Initialisation

This phase can only be applied once a derived or iterative initialisation phases has been implemented. It works off an equilibrium state and uses Cinitial factors that can be estimated to shift the initial population away from an equilibrium state prior to start year. If there is known exploitation before data exists for a population this can be a solution for estimating a non equilibrium population. Note that it may be advisable to include an observation of age composition data for the first year of the model in order to estimate the non equilibrium population state.

### Fixed Initialisation

This is a user defined table that is taken to be the initial partition prior to start year. Users have the ability to initialise models by specify the numbers at age for each category. See initialisation type `state_category_by_age` for how to implement this.

## 4.5. Model run years

Following initialisation, the model then runs over a number of user-defined years from (`initial_year` to `final_year`). For this part of the model, the annual cycle can be broken into separate time-steps, and observations can be associated with the state of the model at the end of any time-step, i.e., likelihoods for particular observations are evaluated, if required, within each time-step.

Processes are carried out in the order specified within each time-step, and can be the same or different to processes in other initialisation phases of the model. The run years define the years over which the model is to run and the annual cycle within each year. The model runs from the start of year `initial` and runs to the end of year `current`. The projection part then extends the run time up to the end of year `final`.

- The time-steps and the processes applied in each

- The initial year (i.e., the model start year)
- The final year (i.e., the model end year)
- The projection final year (i.e., the model projection end year)

## 4.6. Projection years

Projection years follow model run years. Projecting is the process of running the model forwards into the future, using stochastic and or deterministic values for population dynamic parameters, such as recruitments and catches. In a projection run in CASAL2 a model is initialised and run through the model years from `initial` to the `final`. Then, the model is re-run from `initial` to `projection_final_year`, where any parameter can be fixed or drawn from a stochastic process between this time period. CASAL2 does not have default projections. Users must specify them using the `@project` command blocks. This is important for parameters that are year specific such as year class parameters. If there is no `@project` for these parameters, they will not exist after `final_year` processes that call them will cause nonsensical output. Any estimable parameter can be projected forward. Available projection types where parameters are drawn during the projection years are: constant, lognormal, and empirical sampling.

### Constant

A parameter can be fixed during all projection years or can be individually specified for each projection year. This is a deterministic process, where we are assuming the parameter is known without error for future years.

### Empirical Sampling

Parameters that are of type vector or map can be re-sampled with replacement between a year range, for use as projected year values.

### Lognormal

The randomised parameter are lognormally distributed, with mean 1, and specified standard deviation and autocorrelation on the log-scale.  $YCS_i = \exp(X_i)$ , where  $(X_i)$  are generated as a Gaussian process with standard deviation  $\sigma_R$  and mean  $-0.5 \sigma_R$  (so that the mean of the parameter will be 1). If the randomised parameter are modified by an arbitrary multiplier, then the only change is that parameter will have mean  $\mu$ , where  $\mu$  is the multiplier.

## 4.7. Population processes

Population processes are those processes that change the model state. Processes produce changes in the model partition, by adding, removing or moving individuals between ages and/or categories. The population processes include recruitment, ageing, mortality events (e.g., natural and anthropogenic) and category transition processes (i.e., processes that move individuals between categories while preserving their age structure). See Section 4 for a complete list of available processes.

There are two types of processes, processes that occur across multiple time steps in the annual cycle e.g Natural Mortality and Instantaneous Mortality. There are also processes that only occur within the time step they are defined. Each of these processes is carried out in the user-defined prescribed order when initialising the model, and then for a user-defined order in each year in the annual cycle.

#### 4.7.1. Recruitment

Recruitment processes are defined as a process that introduces new individuals into the model. CASAL2 currently implements two types of recruitment process, constant recruitment and Beverton-Holt recruitment (Beverton and Holt, 1957).

In the recruitment processes, the number of individuals are added to a single age class within the partition, with the amount defined by the type of recruitment process and its function. If more than one category is defined, then the proportion of recruiting individuals to be added to each category is specified by the `proportions` parameter. For example, if recruiting to categories labelled male and female, then you might set the proportions as 0.5 and 0.5 respectively to denote that half of the recruits recruit to the male category and the remaining half to the female category.

For the constant and Beverton-Holt recruitment processes, the number of individuals following recruitment in year  $y$  is,

$$N_{i,j} \leftarrow N_{i,j} + p_j(R_y) \quad (4.2)$$

where  $N_{i,j}$  is the numbers in category  $j$  at age  $i$ ,  $p_j$  is the proportion to category  $j$ , and  $R_y$  is the number of recruits for year  $y$ . See below for how  $R_y$  is determined in each of these cases.

##### Constant Recruitment

In the constant recruitment process the total number of recruits added each year is  $R_y$ , and is simply  $R_0$ , i.e.

$$R_y = R_0 \quad (4.3)$$

Constant recruitment recruits a constant number of individuals each year. It is equivalent to a Beverton-Holt recruitment process with steepness set equal to one ( $h = 1$ ).

For example, to specify a constant recruitment process, where individuals are added to male and female immature categories at  $age = 1$ , and the number to add is  $R_0 = 5 \times 10^5$ , then the syntax is

```
@process Recruitment
type constant_recruitment
categories male.immature female.immature
proportions 0.5 0.5
r0 500000
age 1
```

##### Beverton-Holt recruitment

In the Beverton-Holt recruitment process the total number of recruits added each year is  $R_y$ , and is the product of the average recruitment  $R_0$ , the annual year class strength multiplier,  $YCS$ , and the stock-recruit relationship i.e.,

$$R_y = R_0 \times YCS_{y-ssb\_offset} \times SR(SSB_{y-ssb\_offset}) \quad (4.4)$$

where *ssb\_offset* is the number of years offset to link the year class with the year of spawning  $y$ , and  $SR$  is the Beverton-Holt stock-recruit relationship parametrised by the steepness  $h$ ,

$$SR(SSB_y) = \frac{SSB_y}{B_0} / \left( 1 - \frac{5h-1}{4h} \left( 1 - \frac{SSB_y}{B_0} \right) \right) \quad (4.5)$$



Note that the Beverton-Holt recruitment process requires a value for  $B_0$  and  $SSB_y$  to resolve the stock-recruitment relationship. Here, a derived quantity (see Section 4.8) must be defined that provides the annual  $SSB_y$  for the recruitment process.  $B_0$  is then defined as the value of the  $SSB$  at the end of one of the initialisation phases. During initialisation the  $YCS$  multipliers are assumed to be equal to one, and recruitment that happens in the initialisation phases that occur before and during the phase when  $B_0$  is determined is assumed to have steepness  $h = 1$  (i.e. in those initialisation phases, recruitment is simply equal to  $R_0$ ). Recruitment in the initialisation phases after the phase where  $B_0$  was determined follow the Beverton-Holt stock-recruit relationship defined above.  $R_0$  and  $B_0$  have a direct relationship when there are no density dependent processes, for this reason users can choose to initialise models using  $B_0$  or  $R_0$ . In New Zealand  $B_0$  is often used, as biological reference points for managing marine populations is based on a percentage of  $B_0$ .

Year classes are standardised to be equal to one over the period  $S$  defined by standardise  $YCS$  years, i.e., the year classes ( $YCS$ ) for each year of the model are calculated as

$$YCS_i = \begin{cases} Y_i / \text{mean}_{y \in S} & : y \in S \\ Y_i & : y \notin S \end{cases}$$

Note that the an effect of this parameterisation is that  $R_0$  is then defined as the mean estimated recruitment over the years  $S$ , because the mean year class multiplier over these years will always be one.

For example, assume a Beverton-Holt recruitment process, where individuals are added to the category 'immature' at  $age = 1$ , the number to add is  $R_0 = 5 \times 10^5$ . Then `SSB_derived_quantity` is a derived quantity that specifies the total spawning stock biomass, with  $B_0$  the value of the derived quantity at the end of the initialisation phase labelled `phase1`. The  $YCS$  are standardised to have mean one in the period 1994 to 2004, and recruits enter into the model two years following spawning. Then the command specification would be,

```
@process Recruitment
type recruitment_beverton_holt
categories immature
proportions 1.0
r0 500000
b0_initialisation_phase phase1
steepness 0.75
age 1
ssb SSB_derived_quantity
standardise_ycs_years 1994-2004
ycs_years 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006
YCS_values 1 1 1 1 1 1 1 1 1 1 1 1 1
```

Note that the  $SSB$  year used in the Beverton-Holt stock recruitment relationship (`ssb_offset`) is determined by the order of ageing, recruitment, and spawning,

- If recruitment then ageing then spawning, then `ssb_offset` should equal `min_age + 1`.
- If spawning then ageing then recruitment, then `ssb_offset` should equal `min_age - 1`.

If any other order is used, then `ssb_offset` should equal `min_age`.

If you have more than one ageing process and a Beverton-Holt recruitment process you will be warned to set your own `ssb_offset` as CASAL2 will, by default, set it based upon the first ageing process in the annual cycle — which may be not be what was desired.

### 4.7.2. Ageing

The ageing process ‘ages’ individuals — it simply moves all individuals in the named categories  $i$  to the next age class  $j + 1$ , or accumulates them if the last age class is a plus group.

The ageing process is defined as,

$$\text{element}(i, j) \leftarrow \text{element}(i, j - 1) \quad (4.6)$$

except that in the case of the plus group (if defined),

$$\text{element}(i, \text{age}_{\max}) \leftarrow \text{element}(i, \text{age}_{\max}) + \text{element}(i, \text{age}_{\max} - 1). \quad (4.7)$$

For example, to apply ageing to the categories `immature` and `mature`, then the syntax is,

```
@process Ageing
type ageing
categories immature mature
```

Note that ageing is *not* applied by CASAL2 by default. As with other processes, CASAL2 will not apply a process unless its defined and specified as a process within the annual cycle. Hence, it is possible to specify a model where a category is not aged. CASAL2 will not check or otherwise warn if there is a category defined where ageing is not applied.

### 4.7.3. Mortality

Four types of mortality processes are permissible in CASAL2, constant rate, event, biomass-event and instantaneous. These processes remove individuals from the partition, either as a rate, as a total number (abundance), as a biomass of individuals or as a mixture of these. Note that CASAL2 does not (yet) implement the Baranov catch equation. To apply both natural and biomass-event mortality, users can use `mortality_instantaneous`. Note that all mortality processes occur within a mortality block of a time step

#### 4.7.3.1. Constant mortality rate

To specify a constant annual mortality rate ( $M = 0.2$ ) for categories ‘male’ and ‘female’, then,

```
@process NaturalMortality
type mortality_constant_rate
categories male female
selectivities One One
m 0.2 0.2
```

$$D_{j,t} = \sum_a N_{a,j} (1 - \exp S_{a,j} M_j p_t) \quad (4.8)$$

Where,  $D_{j,t}$  is the number of deaths in category  $j$  in time step  $t$ ,  $N_{a,j}$  is the number of individuals in category  $j$  at age  $a$ .  $S_{a,j}$  is the selectivity value for age  $a$  in category  $j$ ,  $M_j$  is the mortality rate for category  $j$ , and  $p_t$  is the proportion of the mortality rate to apply in time step  $t$ .

Note that the mortality rate process requires a selectivity. To apply the same mortality rate over all age classes, use a selectivity defined as  $S_j = 1.0$  for all ages  $j$ , e.g.,

```
@selectivity One
type constant
c 1
```

#### 4.7.3.2. Event and biomass-event mortality

The event mortality process and biomass mortality processes act in a similar manner, except that they remove a specified abundance (number of individuals) or biomass respectively. These can be used to include anthropogenic mortality where numbers of removals are known, for example, fishing in a fisheries model, rather than applying mortality as a rate.

In these cases, the abundance or biomass removed is also constrained by a maximum exploitation rate. CASAL2 removes as many individuals or as much biomass as it can while not exceeding the maximum exploitation rate. When minimising, event mortality processes require a penalty to discourage parameter values that do not allow the defined number of individuals to be removed. Here, the model penalises those parameter estimates that result in an too low a number of individuals in the defined categories (after applying selectivities) to allow for removals at the maximum exploitation rate. See Section 5.8 for more information on how to specify penalties.

For example, the event mortality applied to user-defined categories  $i$ , with the numbers removed at age  $j$  determined by a selectivity-at-age  $S_j$  is applied as follows:

First, calculate the vulnerable abundance for each category  $i$  in  $1 \dots I$  for ages  $j = 1 \dots J$  that are subject to event mortality,

$$V(i, j) = S(j)N(i, j) \quad (4.9)$$

And hence define the total vulnerable abundance  $V_{total}$  as,

$$V_{total} = \sum_i \sum_j V(i, j) \quad (4.10)$$

Hence the exploitation rate to apply is

$$U = \begin{cases} C/V_{total}, & \text{if } C/V_{total} \leq U_{max} \\ U_{max}, & \text{otherwise} \end{cases} \quad (4.11)$$

And the number removed  $R$  from each age  $j$  in category  $i$  is,

$$R(i, j) = UV(i, j) \quad (4.12)$$

For example, to specify fishing mortality in a fisheries model, with catches given for a set of specific years, over categories 'immature' and 'mature', with selectivity 'FishingSel' and assuming a maximum possible exploitation rate of 0.7, then the syntax would be,

```
@process Fishing
type event_mortality
categories immature mature
years 2000 2001 2002 2003
U_max 0.70
selectivities FishingSel FishingSel
penalty event_mortality_penalty
```

#### 4.7.3.3. Instantaneous mortality

The instantaneous mortality process is a process that combines both natural mortality and event biomass mortality into a single process. This allows the natural mortality to occur across multiple time steps, and can specify multiple instances of event mortality to account for, say, multiple fisheries operating sequentially or concurrently. This process applies half the natural mortality in each time step, then the mortalities from all the concurrent fisheries instantaneously, then the remaining half of the natural mortality.

When instantaneous mortality is applied the following equations are used.

- An exploitation rate (actually a proportion) is calculated for each fishery, as the catch over the selected-and-retained biomass,

$$U_f = \frac{C_f}{\sum_j \bar{w}_j S_{f,j} n_j e^{-0.5tM_j}}$$

- The fishing pressure associated with fishery  $f$  is defined as the maximum proportion of fish taken from any element of the partition in the area affected by fishery  $f$ ,

$$U_{f,obs} = \max_j (\sum_k S_{k,j} U_k)$$

where the maximum is over all partition elements affected by fishery  $f$ , and the summation is over all fisheries  $k$  which affect the  $j$ th partition element in the same time step as fishery  $f$ .

In most cases the fishing pressure will be equal to the exploitation rate (i.e.,  $U_{f,obs} = U_f$ ), but they can be different if (a) there is another fishery operating in the same time step as fishery  $f$  and affecting some of the same partition elements, and/or (b) the selectivity  $S_{f,j}$  does not have a maximum value of 1.

There is a maximum fishing pressure limit of  $U_{f,max}$  for each fishery  $f$ . So, no more than proportion  $U_{f,max}$  can be taken from any element of the partition affected by fishery  $f$  in that time step. Clearly  $0 \leq U_{max} \leq 1$ . It is an error if two fisheries which affect the same partition elements in the same time step do not have the same  $U_{max}$ .

For each  $f$ , if  $U_{f,obs} > U_{f,max}$ , then  $U_f$  is multiplied by  $U_{f,max}/U_{f,obs}$  and the fishing pressures are recalculated. In this case the catch actually taken from the population in the model will differ from the specified catch,  $C_f$ .

- The partition is updated using

$$n'_j = n_j \exp(-tM_j) [1 - \sum_f S_{f,j} U_f]$$

An example of the syntax is if we want to apply natural mortality of 0.20 across three time steps on both male and female categories. And we have two fisheries FishingWest FishingEast with there respective catches known for years 1975:1977 in kilograms. These are given in the `catches` table and information on selectivities, penalties and maximum exploitation rates are given in the `fisheries` table.

```
@process instant_mort
type mortality_instantaneous
m 0.20
time_step_ratio 0.42 0.25 0.33
selectivities One
```

```
categories male female
units kgs
```

```
table catches
year FishingWest FishingEast
1975 80000 111000
1976 152000 336000
1977 74000 1214000
end table
```

```
table fisheries
fishery      category  selectivity u_max  time_step penalty
FishingWest  stock      westFSel    0.7   step1    CatchPenalty
FishingEast  stock      eastFSel    0.7   step1    CatchPenalty
end_table
```

#### 4.7.3.4. Hollings Rate

The density-dependent Holling mortality process applies the Holling Type II and Type III functions (Holling, 1959), but is generalised using the Michaelis-Menten equation (Michaelis and Menten, 1913). The function removes a number or biomass from a set of categories according to their total (selected) abundance (or biomass) and some 'predator' abundance (or biomass), but constrained by a maximum exploitation rate.

For example, the mortality applied to user-defined categories  $k$ , with the numbers removed at age  $l$  determined by a selectivity-at-age  $S(l)$  is applied as follows:

First, calculate the total predator abundance (or biomass) over all predator categories  $k$  in  $1 \dots K$  and ages  $l = 1 \dots L$  that are applying the mortality,

$$P(k, l) = S_{predator}(l) N_{predator}(k, l) \quad (4.13)$$

And define the total predator abundance (or biomass)  $P_{total}$  as,

$$P_{total} = \sum_K \sum_L P(k, l) \quad (4.14)$$

Then, calculate the total vulnerable abundance (or biomass) over all prey categories  $k$  in  $1 \dots K$  and ages  $l = 1 \dots L$  that are subject to the mortality,

$$V(k, l) = S_{prey}(l) N_{prey}(k, l) \quad (4.15)$$

And hence define the total vulnerable abundance (or biomass)  $V_{total}$  as,

$$V_{total} = \sum_K \sum_L V(k, l) \quad (4.16)$$

and then, the the number to remove is determined as,

$$R_{total} = P_{total} \frac{a V_{total}^{x-1}}{b + V_{total}^{x-1}} \quad (4.17)$$

where  $x = 2$  for Holling type II function,  $x = 3$  for Holling type III function, or any value of  $x \geq 1$  for the generalised Michaelis-Menten function, and  $a > 0$  and  $b > 0$  are the Holling function parameters.

Hence the exploitation rate to apply is

$$U = \begin{cases} R_{total}/V_{total}, & \text{if } R_{total}/V_{total} \leq U_{max} \\ U_{max}, & \text{otherwise} \end{cases} \quad (4.18)$$

And the number removed  $R$  from each age  $l$  in category  $k$  is,

$$R(k,l) = UV(k,l) \quad (4.19)$$

The density-dependent Holling mortality process is applied either as a biomass or an abundance depending on the value of the `is_abundance` switch.

For example, a biomass Holling type II mortality process on `prey` by our predator `predator` would have syntax,

```
@process HollingMortality
type Holling_mortality_rate
is_abundance F
a 0.08
b 10000
x 2
categories prey
selectivities One
predator_categories predator
predator_selectivities One
u_max 0.8
```

#### 4.7.4. Transition By Category

This process covers moves individuals between categories. Because the CASAL2 partition user defined, this type of process is used to move individuals between categorised, and is used to specify processes such as maturation (move individuals from an immature to mature state) or migration (move individuals from one area to another).

##### 4.7.4.1. Annual transition by category

A special case is annual transition by category, which allows a transition to occur in a specific subset of years only, where each year can have a different rate.

In both cases, there has to be a one to one relationship between the ‘from’ category and the ‘to’ category — for every source category there is one target category. If however, you want to merge categories, then just repeat the ‘to’ category multiple times.

$$N_{a,j} = N_{a,i} \times P_i \times S_{a,i} \quad (4.20)$$

where  $N_{a,j}$  is the number of individuals that have moved to category  $j$  from category  $i$  in age  $a$  and  $N_{a,i}$  is the number of individuals in category  $i$ .  $P_i$  is the proportion parameter for category  $i$  and  $S_{a,i}$  is the selectivity at age  $a$  for category  $i$ .

An example, to specify a simple spawning migration of mature males from a western area migrating to an eastern (spawning) area, then the syntax is

```
@process Spawning_migration
type category_transition
from West.males
to East.males
selectivities MatureSel
proportions 1
```

Where `MatureSel` is a selectivity that describes the proportion of age or length classes that are mature and thus move to the eastern area.

#### 4.7.5. Tag Release events

Tagging processes can be age or length based processes, where by numbers of fished are moved from an untagged category to a tagged category that the user has defined in the `@Categories` block. Tag release processes can also account for tag induced mortality on individuals. Age based tag release events take a known number of individuals tagged for each age and do a straightforward category transition along with extra mortality. Length based tag release processes are more complicated, as CASAL2 needs to calculate the age length matrix and exploitation by each length to then move the correct numbers at age based on a length input.

#### 4.7.6. Tag Loss

Tag Loss is the process where tags are lost from tagged categories over time from tag failure or getting knocked off. This process is applied as a instantaneous mortality rate that can happen over multiple time steps in the annual cycle. This method assumes when tags are lost that the fish is removed from the partition. All though this seems logically incorrect, we are dealing with such a small number of fish that the impact is minimal and computationally simpler. Note that if your tagging events make up a large proportion of the population you may want to adjust this method. There will be two types of tag loss processes that are termed `single` and `double`. Currently only `single` exists in CASAL2. `double` will deal with situations where a tag release process tags individuals with two tags. In which there is another formulae to work out the rate of tag loss.

```
@process Tag_loss
type tag_loss
categories tagged_fish
tag_loss_rate 0.02
time_step_ratio 0.25 0.75
selectivities One
tag_loss_type single
year 1985
```

### 4.8. Derived quantities

Some processes require, as arguments, a population value derived from the population state. These are termed *derived quantities*. Derived quantities are values, calculated by CASAL2 at the end of a specified time-step in every year, and hence they have a single value for each year of the model. Derived quantities can be calculated as either an abundance or as a biomass. Abundance derived quantities are simply the count or sum of categories (after applying a selectivity). Biomass derived quantities are similar, except they are a measure of biomass. Derived quantities are also calculated during the initialisation phases, and hence the time-step during each phase must also be specified. If

the initialisation time-steps are not specified, CASAL2 will calculate the derived quantity during the initialisation phases in every year, at the end of the annual cycle.

Derived quantities are required by some processes, for example the Beverton-Holt recruitment process. The Beverton-Holt recruitment process can require an equilibrium biomass ( $B_0$ ) and annual spawning stock biomass values ( $SSB_y$ ) to resolve the stock-recruit relationship. Here, these would be defined as the abundance or biomass of a part of the population at some point in the annual cycle for selected ages and categories, and would be calculated as a derived quantity.

Derived quantities are associated with a mortality block see section 4.4 for more detail on mortality blocks. Users can ask for derived quantities partway through mortality blocks. Currently two methods are implemented in CASAL2 to interpolate derived quantities part-way through a mortality block, these are `weighted_sum` and `weighted_product`, they are defined as,

- `weighted_sum`: after proportion  $p$  of the mortality block, the partition elements are given by  $n_{p,j} = (1-p)n_j + p'n'_j$
- `weighted_product`: after proportion  $p$  of the mortality block, the partition elements are given by  $n_{p,j} = n_j^{1-p} n_j'^p$

where,  $n_{p,j}$  is the derived quantity at proportion  $p$  of the mortality block for category  $j$ .  $n_j$  is the quantity at the beginning of the mortality block and  $n'_j$  is the quantity at the end of the mortality block.

As an example, to define a biomass derived quantity (say spawning stock biomass, SSB) for a model, evaluated at the end of the first time-step (labelled `step_one`), over all 'mature' male and female categories and halfway through the mortality block using the `weighted_sum` method, we would use the syntax,

```
@derived_quantity SSB
type biomass
time_step step_one
categories mature.male mature.female
selectivities One
time_step_proportion 0.5
time_step_proportion_method weighted_sum
```

#### 4.9. Age-length relationship

The age-length relationship defines the length at age (and the weight at length, see Section 4.9) of individuals at age/category within the model. There are three length-age relationships available in CASAL2. The first is the naive no relationship (where each individual has length 1 irrespective of age). The second and third are the von-Bertalanffy and Schnute relationships respectively. The length-at-age relationship is used to determine the length frequency, given age, and then with the length-weight relationship, a weight-at-age of individuals within an age/category.

The three age-length relationships are,

None: where the length of each individual is exactly 1 for all ages, in which case the `none` length-weight relationship must also be used.

von Bertalanffy: where length at age is defined as,

$$\bar{s}(age) = L_{\infty} (1 - \exp(-k(age - t_0))) \quad (4.21)$$



Schnute: where length at age is defined as,

$$\bar{s}(\text{age}) = \begin{cases} \left[ y_1^b + (y_2^b - y_1^b) \frac{1 - \exp(-a(\text{age} - \tau_1))}{1 - \exp(-a(\tau_2 - \tau_1))} \right]^{1/b}, & \text{if } a \neq 0 \text{ and } b \neq 0 \\ y_1 \exp \left[ \ln(y_2/y_1) \frac{1 - \exp(-a(\text{age} - \tau_1))}{1 - \exp(-a(\tau_2 - \tau_1))} \right], & \text{if } a \neq 0 \text{ and } b = 0 \\ \left[ y_1^b + (y_2^b - y_1^b) \frac{\text{age} - \tau_1}{\tau_2 - \tau_1} \right]^{1/b}, & \text{if } a = 0 \text{ and } b \neq 0 \\ y_1 \exp \left[ \ln(y_2/y_1) \frac{\text{age} - \tau_1}{\tau_2 - \tau_1} \right], & \text{if } a = 0 \text{ and } b = 0 \end{cases} \quad (4.22)$$

The von Bertalanffy curve is parameterised by  $L_\infty$ ,  $k$ , and  $t_0$ ; the Schnute curve (Schnute, 1981) by  $y_1$  and  $y_2$ , which are the mean lengths at reference ages  $\tau_1$  and  $\tau_2$ , and  $a$  and  $b$  (when  $b = 1$ , this reduces to the von Bertalanffy with  $k = a$ ).

When defining length-at-age in CASAL2, you must also define a length-weight relationship (see Section 4.9 below).

### Calculation of length-at-age (in an age-based model)

#### Interpolation of length-at-age

#### Size-weight relationship

There are two length-weight relationships available in CASAL2. The first is the naive no relationship. Here, the weight of an individual, regardless of length, is always 1. The second is the basic relationship.

The two length-weight relationships are,

- None: The length-weight relationship where

$$\text{mean weight} = 1 \quad (4.23)$$

- Basic: The length-weight relationship where the mean weight  $w$  of an individual of length  $l$  is

$$w = al^b \quad (4.24)$$

Note that if a distribution of length-at-age is specified, then the mean weight is calculated over the distribution of lengths, and is

$$w = (al^b)(1 + cv^2)^{\frac{b(b-1)}{2}} \quad (4.25)$$

where the  $cv$  is the c.v. of lengths-at-age. This adjustment is exact for lognormal distributions, and a close approximation for normal distributions if the c.v. is not large (Bull et al., 2012).

Be careful about the scale of  $a$  — this can easily be specified incorrectly. If the catch is in tonnes and the growth curve in centimetres, then  $a$  should be on the right scale to convert a length in centimetres to a weight in tonnes. Note that there are reports available that can be used to help check that the units specified are plausible (see Section ??).

## Calculation of mean weight

### 4.10. Weightless model

### 4.11. Maturity, in models without maturing in the partition

If maturity is not a character of the partition it can easily be derived at in instance in time using selectivities. Applying a maturity selectivity on to the partition allows CASAL2 to use mature elements in processes, derive mature biomasses estimates (using derived quantities), and report the mature partition as an output.

### 4.12. Selectivities

A selectivity is a function that can have a different value for each age class. Selectivities are used throughout CASAL2 to interpret observations (Section 5) or to modify the effects of processes on each age class (Section 4). CASAL2 implements a number of different parametric forms, including logistic, knife edge, and double normal selectivities. Selectivities are defined in there own command block (@selectivity), where the unique label is used by observations or processes to identify which selectivity to apply.

Selectivities are indexed by age, with indices from `min_age` to `max_age`. For example, you might have an age-based selectivity that was logistic with 50% selected at age 5 and 95% selected at age 7. This would be defined by the `type=logistic` with parameters  $a_{50} = 5$  and  $a_{0.95} = (7 - 5) = 2$ . Then the value of the selectivity at age  $x = 7$  is 0.95 and the selectivity at  $x = 3$  is 0.05. Note selectivities can be length based, However Caution, more testing is needed for this functionality.

Note that the function values for some choices of parameters for some selectivities can result in an computer numeric overflow error (i.e., the number calculated from parameter values is either too large or too small to be represented in computer memory). CASAL2 implements range checks on some parameters to test for a possible numeric overflow error before attempting to calculate function values. For example, the logistic selectivity is implemented such that if  $(a_{50} - x)/a_{0.95} > 5$  then the value of the selectivity at  $x = 0$ , i.e., for  $a_{50} = 5$ ,  $a_{0.95} = 0.1$ , then the value of the selectivity at  $x = 1$ , without range checking would be  $7.1 \times 10^{-52}$ . With range checking, that value is 0 (as  $(a_{50}x)/a_{0.95} = 40 > 5$ ).

The available selectivities are;

- Constant
- Knife-edge
- All values
- All values bounded
- Increasing
- Logistic
- Inverse logistic
- Logistic producing
- Double normal
- Double exponential
- Cubic spline (Not yet implemented)

The available selectivities are described below.

#### 4.12.1. constant

$$f(x) = C \quad (4.26)$$

The constant selectivity has the estimable parameter  $C$ .

#### 4.12.2. knife\_edge

$$f(x) = \begin{cases} 0, & \text{if } x < E \\ \alpha, & \text{if } x \geq E \end{cases} \quad (4.27)$$

The knife-edge ogive has the estimable parameter  $E$  and a scaling parameter  $\alpha$ , where the default value of  $\alpha = 1$

#### 4.12.3. all\_values

$$f(x) = V_x \quad (4.28)$$

The all-values selectivity has estimable parameters  $V_{low}, V_{low+1} \dots V_{high}$ . Here, you need to provide the selectivity value for each age class.

#### 4.12.4. all\_values\_bounded

$$f(x) = \begin{cases} 0, & \text{if } x < L \\ V_x, & \text{if } L \leq x \leq H \\ V_H, & \text{if } x > H \end{cases} \quad (4.29)$$

The all-values-bounded selectivity has non-estimable parameters  $L$  and  $H$ . The estimable parameters are  $V_L, V_{L+1} \dots V_H$ . Here, you need to provide an selectivity value for each age class from  $L \dots H$ .

#### 4.12.5. increasing

$$f(x) = \begin{cases} 0, & \text{if } x < L \\ f(x-1) + \pi_x(\alpha - f(x-1)), & \text{if } L \leq x \leq H \\ f(\alpha), & \text{if } x \geq H \end{cases} \quad (4.30)$$

The increasing ogive has non-estimable parameters  $L$  and  $H$ . The estimable parameters are  $\pi_L, \pi_{L+1} \dots \pi_H$  (but if these are estimated, they should always be constrained to be between 0 and 1).  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . Note that the increasing ogive is similar to the all-values-bounded ogive, but is constrained to be non-decreasing.

**4.12.6. logistic**

$$f(x) = \alpha / [1 + 19^{(a_{50}-x)/a_{t095}}] \quad (4.31)$$

The logistic selectivity has estimable parameters  $a_{50}$  and  $a_{t095}$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . The logistic selectivity takes values  $0.5\alpha$  at  $x = a_{50}$  and  $0.95\alpha$  at  $x = a_{50} + a_{t095}$ .

**4.12.7. inverse\_logistic**

$$f(x) = \alpha - \alpha / [1 + 19^{(a_{50}-x)/a_{t095}}] \quad (4.32)$$

The inverse logistic selectivity has estimable parameters  $a_{50}$  and  $a_{t095}$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . The logistic selectivity takes values  $0.5\alpha$  at  $x = a_{50}$  and  $0.95\alpha$  at  $x = a_{50} - a_{t095}$ .

**4.12.8. logistic\_producing**

$$f(x) = \begin{cases} 0, & \text{if } x < L \\ \lambda(L), & \text{if } x = L \\ (\lambda(x) - \lambda(x-1)) / (1 - \lambda(x-1)), & \text{if } L < x < H \\ 1, & \text{if } x \geq H \end{cases} \quad (4.33)$$

The logistic-producing selectivity has the non-estimable parameters  $L$  and  $H$ , and has estimable parameters  $a_{50}$  and  $a_{t095}$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . For category transitions,  $f(x)$  represents the proportion moving, not the proportion that have moved. This selectivity was designed for use in an age-based model to model maturity. In such a model, a logistic-producing maturation selectivity will (in the absence of other influences) make the proportions mature follow a logistic curve with parameters  $a_{50}$ ,  $a_{t095}$ .

**4.12.9. double\_normal**

$$f(x) = \begin{cases} \alpha 2^{-[(x-\mu)/\sigma_L]^2}, & \text{if } x \leq \mu \\ \alpha 2^{-[(x-\mu)/\sigma_R]^2}, & \text{if } x \geq \mu \end{cases} \quad (4.34)$$

The double-normal selectivity has estimable parameters  $a_1$ ,  $s_L$ , and  $s_R$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . It has values  $\alpha$  at  $x = a_1$ , and  $0.5\alpha$  at  $x = a_1 - s_L$  and  $x = a_1 + s_R$ .

**4.12.10. double\_exponential**

$$f(x) = \begin{cases} \alpha y_0 (y_1/y_0)^{(x-x_0)/(x_1-x_0)}, & \text{if } x \leq x_0 \\ \alpha y_0 (y_2/y_0)^{(x-x_0)/(x_2-x_0)}, & \text{if } x > x_0 \end{cases} \quad (4.35)$$

The double-exponential selectivity has non-estimable parameters  $x_1$  and  $x_2$ , and estimable parameters  $x_0$ ,  $y_0$ ,  $y_1$ , and  $y_2$ .  $\alpha$  is a scaling parameter, with default value of  $\alpha = 1$ . It can be ‘U-shaped’. Bounds for  $x_0$  must be such that  $x_1 < x_0 < x_2$ . With  $\alpha = 1$ , the selectivity passes through the points  $(x_1, y_1)$ ,  $(x_0, y_0)$ , and  $(x_2, y_2)$ . If both  $y_1$  and  $y_2$  are greater than  $y_0$  the selectivity is ‘U-shaped’ with minimum at  $(x_0, y_0)$ .

#### 4.12.11. spline

Not yet implemented, The spline selectivity implements a cubic spline that has non-estimable knots, and an estimable value for each knot. The cubic spline is either (i) a natural splines where the second derivatives are set to 0 at the boundaries, i.e., the values at the boundaries are horizontal, (ii) a spline with a fixed first derivative at the boundaries (linear, but not necessarily horizontal) and (iii) spline which turns into a parabola at the boundaries.

### 4.13. Time Varying Parameters

CASAL2 has the functionality to vary a parameter annually between the start and final year of a model run. This can be for blocks of years or specific years if chosen. For years that are not specified the parameter will default to the input or if in a iterative state such as estimation mode, the value being trialled at that iteration. Available methods for time varying a parameter. Where this functionality will become quite useful is in simulating more realistic observations. When you allow fisheries to have annual varying catchabilities and other more realistic model components simulated observations become more real data and thus conclusions based on simulated data are more useful.

#### 4.13.1. Constant

Allows a parameter to have an alternative values during certain years, which can be estimated.

```
@time_varying q_time_var
type constant
parameter catchability[survey_q].q
years 1975:1988
value 0.001
```

#### 4.13.2. Random Walk

A random deviate added into the last value drawn from a standard normal distribution. This has an estimable parameter  $\sigma_p$  for each time varying parameter  $p$ . For reproducible modelling, it is highly recommended that users set the seed (see Section 3.4) when using stochastic functionality like this, otherwise reproducing models becomes almost impossible.

```
@time_varying q_time_var
type random_walk
parameter catchability[survey_q].q
distribution normal
mean 0
sigma 3
```

If the parameter specified in the @time\_varying is associated with an @estimate block then the parameter is constrained to stay within the lower and upper bounds of the @estimate block. Warning, if the parameter does not have an associated @estimate block then there is no safe guard for a random deviate to put the parameter in a space where the model fails, i.e generates NA or INF values. to avoid this from happening it is recommended you specify an @estimate block even though you are not estimating the parameter like below.

```
@estimate survey_q_est
```

```

type uniform
parameter catchability[survey_q].q
lower_bound 1e-6
upper_bound 10

```

This will insure the random walk time varying process will set the any new candidate within the lower and upper bound of the @estimate block.

#### 4.13.3. Annual shift

A parameter generated in year  $y$  ( $\theta'_y$ ) depends on the value specified by the user ( $\theta_y$ ) along with three coefficients  $a, b$  and  $c$  as follows,

$$\bar{\theta}_y = \frac{\sum_y^Y \theta_y}{Y} \quad (4.36)$$

$$\theta'_y = a\bar{\theta}_y + b\bar{\theta}_y^2 + c\bar{\theta}_y^3 \quad (4.37)$$

#### 4.13.4. Exogenous

parameters are shifted based on an exogenous variable, an example of this is an exploitation selectivity parameters that may vary between years based on known changes in exploitation behaviour such as season, start time, and average depth of exploitation.

$$\delta_y = a(E_y - \bar{E}) \quad (4.38)$$

$$\theta'_y = \theta_y + \delta_y \quad (4.39)$$

where  $\delta_y$  is the shift or deviation in parameter  $\theta_y$  in year  $y$  to generate the new parameter value in year  $y$  ( $\theta'_y$ ).  $a$  is an estimable shift parameter,  $E$  is the exogenous variable and  $E_y$  is the value of this variable in year  $y$ . For more information readers can see Francis et al. (2003).

---

## 5. The estimation section

### 5.1. Role of the estimation section

The role of the estimation section is to define the tasks carried out by CASAL2:

1. Define the objective function (see Section 5.2)
2. Define the parameters to be estimated (see Section 5.3)
3. Calculate a point estimate, i.e., the maximum posterior density estimate (MPD) (see Section 5.4).
4. Calculate a posterior profile selected parameters, i.e., find, for each of a series of values of a parameter, allowing the other estimated parameters to vary, the minimum value of the objective function (see Section 5.5).
5. Generate an MCMC sample from the posterior distribution (see Section 5.6).
6. Calculate the approximate covariance matrix of the parameters as the inverse of the minimizer's approximation to the Hessian, and the corresponding correlation matrix (see Section 5.4).

The estimation section defines the objective function, parameters of the model, and the method of estimation (point estimates, Bayesian posteriors, profiles, etc.). The objective function is based on a goodness-of-fit measure of the model to observations, priors and penalties. See the observation section for a description of the observations, likelihoods, priors and penalties.

### 5.2. The objective function

In Bayesian estimation, the objective function is a negative log-posterior,

$$Objective(p) = -\sum_i \log [L(\mathbf{p}|O_i)] - \log [\pi(\mathbf{p})] \quad (5.1)$$

where  $\pi$  is the joint prior density of the parameters  $p$ .

The contribution to the objective function from the likelihoods are defined in Section 6.1. In addition to likelihoods, priors (see Section 5.7) and penalties (see Section 5.8) are components of the objective function.

Penalties can be used to ensure that the exploitation rate constraints on mortality events (i.e., fisheries) are not breached (otherwise there is nothing to prevent the model from having abundances so low that the recorded mortalities could not have been taken), penalties on category transitions (to ensure there are enough individuals to move), and possibly penalties to encourage estimated values to be similar or smooth, etc. Equation 5.1 can mathematically reduce to a penalised likelihood equation if all priors are assumed to be uniform. This is because uniform priors have a zero contribution to the objective function so Equation 5.1 reduces to likelihoods plus penalties.

### 5.3. Specifying the parameters to be estimated

The estimable parameters that will be estimated are defined using `@estimate` commands (see Section 9). An `@estimate` command-block looks like,

```
@estimate process[NaturalMortality].m
lower_bound 0.1
upper_bound 0.4
type uniform
```

See Section 3.5.5 for instructions on how to generate the parameter name. At least one parameter is to be estimated if doing an estimation `-e`, profile `-p`, or MCMC `-m` run. Initial values for the parameters to be estimated will still need to be provided, and these are used as the starting values for the minimiser. However, these may be overwritten if you provide a set of alternative starting values (i.e., using `casal2 -i`, see Section 3.4).

All parameters are estimated within bounds. For each parameter to be estimated, you need to specify the bounds and the prior (`type`) (Section 5.7). Note that the bounds and prior for each parameter refer to the values of the parameters, not the actual values resulting from the application of the parameter to an equation. Bounds should be carefully chosen as they effect the space in which the minimisers search over. Some minimisers convert lower and upper bound into a minimisation space (for example `-1,1` space for the numerical differences algorithm). If estimating only some elements of a vector, either define each element of the vector to be estimated (see 3.5.5) or fix the others by setting the bounds equal.

## 5.4. Point estimation

Point estimation is invoked with `casal2 -e`. Mathematically, it is an attempt to find a minimum of the objective function. CASAL2 has multiple algorithms for solving (minimising) the optimisation problem. There are three non auto differential minimisers: numerical differences (GAMMA DIFF), differential evolution minimiser, and the `dlib` minimiser. There are also three auto differential minimisers being: ADOL-C, CPPAD, and BETADIFF. For references see section 1.3

### 5.4.1. The numerical differences minimiser

The minimiser has three kinds of (non-error) exit status, depending on the minimiser:

1. Successful convergence (suggests you have found a local minimum, at least).
2. Convergence failure (you have not reached a local minimum, though you may deem yourself to be ‘close enough’ at your own risk).
3. Convergence unclear (the minimiser halted but was unable to determine if convergence occurred. You may be at a local minimum, although you should check by restarting the minimiser at the final values of the estimated parameters).

You can choose the maximum number of quasi-Newton iterations and objective function evaluations allotted to the minimiser. If it exceeds either limit, it exits with a convergence failure. We recommend large numbers of evaluations and iterations (at least the defaults of 300 and 1000) unless you successfully reach convergence with less. You can also specify an alternative starting point of the minimiser using `casal2 -i`.

We want to stress that the minimisers are local optimisation algorithms trying to solve a global optimisation problem. What this means is that, even if you get a ‘successful convergence’ message, your solution may be only a local minimum, not a global one. To diagnose this problem, try doing multiple runs from different starting points and comparing the results, or doing profiles of one or



more key parameters and seeing if any of the profiled estimates finds a better optimum than the original point estimate.

The approximate covariance matrix of the estimated parameters can be calculated as the inverse of the minimiser's approximation to the Hessian, and the corresponding correlation matrix is also calculated. Be aware that

- the Hessian approximation develops over many minimiser steps, so if the minimiser has only run for a small number of iterations the covariance matrix can be a very poor approximation
- the inverse Hessian is not a good approximation to the covariance matrix of the estimated parameters, and may not be useful to construct, for example, confidence intervals.

Also note that if an estimated parameter has equal lower and upper bounds, it will have entries of '0' in the covariance matrix and NaN or -1.#IND (depending on the operating system) in the correlation matrix.

```
@minimiser numerical_diff
type numerical_differences
tolerance 1e-6
iterations 2500
evaluations 4000
```

#### 5.4.2. The differential evolution minimiser

The differential evolution minimiser is a simple population based, stochastic function minimizer, but is claimed to be quite powerful in solving minimisation problems. It is a method of mathematical optimization of multidimensional functions and belongs to the class of evolution strategy optimizers. Initially, the procedure randomly generates and evaluates a number of solution vectors (the population size), each with  $p$  parameters. Then, for each generation (iteration), the algorithm creates a candidate solution for each existing solution by random mutation and uniform crossover. The random mutation generates a new solution by multiplying the difference between two randomly selected solution vectors by some scale factor, then adding the result to a third vector. Then an element-wise crossover takes place with probability  $P_{cr}$ , to generate a potential candidate solution. If this is better than the initial solution vector, it replaces it, otherwise the original solution is retained. The algorithm is terminated after either a predefined number of generations (`max_generations`) or when the maximum difference between the scaled individual parameters from the candidate solutions from all populations is less than some predefined amount `tolerance`.

The differential evolution minimiser can be good at finding global minimums in surfaces that may have local minima. However, the speed of the minimiser, and the ability to find a good minima depend on the number of initial 'populations'. Some authors recommend that the number of populations be set at about  $10 * p$ , where  $p$  is the number of free parameters. However, depending on your problem, you may find that you may need more, or that less will suffice.

We note that there is no proof of convergence for the differential evolution solver, but several papers have found it to be an efficient method of solving multidimensional problems. Our (limited) experience suggests that it can often find a better minima and may be faster or longer (depending on the actual model specification) at finding a solution when compared with the numerical differences minimiser. Comparisons with auto-differentiation minimisers or other more sophisticated algorithms have not been made.

```
@minimiser DE_solver
```

```
type de_solver
tolerance 1e-6
iterations 2500
evaluations 4000
```

### 5.4.3. Betadiff minimiser

An auto-differentiable minimiser for non-linear models, This is the minimiser from the original CASAL package.

```
@minimiser beta_diff
type beta_diff
tolerance 1e-6
iterations 2500
evaluations 4000
```

### 5.4.4. ADOL-C minimiser

An auto-differentiable minimiser for non-linear models.

```
@minimiser ADOLC
type adolc
tolerance 1e-6
iterations 2500
evaluations 4000
```

### 5.4.5. CPPAD minimiser

An auto-differentiable minimiser for non-linear models.

```
@minimiser CPPAD
type cppad
tolerance 1e-6
iterations 2500
evaluations 4000
```

### 5.4.6. Dlib minimiser

Non auto-diff minimiser

```
@minimiser Dlib
type dlib
tolerance 1e-6
iterations 2500
evaluations 4000
```

## 5.5. Posterior profiles

If profiles are requested `casal2 -p`, CASAL2 will first calculate a point estimate. For each scalar parameter or, in the case of vectors or selectivities, the element of the parameter to be profiled,

CASAL2 will fix its value at a sequence of  $n$  evenly spaced numbers (*step*) between a specified lower and upper bounds  $l$  and  $u$ , and calculate a point estimate at each value.

By default  $step = 10$ , and  $(l, u) = (\text{lower bound on parameter plus } (range/(2n)), \text{upper bound on parameter less } (range/(2n)))$ . Each minimisation starts at the final parameter values from the previous resulting value of the parameter being profiled. CASAL2 will report the objective function for each parameter value. Note that an initial point estimate should be compared with the profile, not least to check that none of the other points along the profile have a better objective function value than the initial ‘minimum’.

You specify which parameters are to be profiled, and optionally the number of steps, lower bound, and upper bound for each. In the case of vector parameters, you will also need to specify the element of the vector being profiled.

You can also supply the initial starting point for the estimation using `casal2 -i file` — this may improve the minimiser performance for the profiles.

If you get an implausible profile, it may be a result of not using enough iterations in the minimiser or a poor choice of minimiser control variables (e.g., the minimiser tolerance). It also may be useful to try both if the minimisers in CASAL2 and compare the results.

## 5.6. Bayesian estimation

CASAL2 can use a Monte Carlo Markov Chain (MCMC) to generate a sample from the posterior distribution of the estimated parameters `casal2 -m` and output the sampled values to a file (optionally keeping only every  $n$ th set of values).

As CASAL2 has no post-processing capabilities. CASAL2 cannot produce MCMC convergence diagnostics (use a package such as BOA) or plot/summarize the posterior distributions of the output quantities (for example, using a general-purpose statistical or spreadsheet package such as S-Plus, R, or Microsoft Excel).

Bayesian methodology and MCMC are both large and complex topics, and we do not describe either properly here. See Gelman et al. (1995) and Gilks et al. (1994) for details of both Bayesian analysis and MCMC methods. In addition, see Punt & Hilborn (2001) for an introduction to quantitative fish stock assessment using Bayesian methods.

This section only briefly describes the MCMC algorithms used in CASAL2. See Section 9.3 for a better description of the sequence of CASAL2 commands used in a full Bayesian analysis.

CASAL2 uses a straightforward implementation of the Metropolis-Hastings algorithm (Gelman et al., 1995, Gilks et al., 1994). The Metropolis-Hastings algorithm attempts to draw a sample from a Bayesian posterior distribution, and calculates the posterior density  $\pi$ , scaled by an unknown constant. The algorithm generates a ‘chain’ or sequence of values. Typically the beginning of the chain is discarded and every  $N$ th element of the remainder is taken as the posterior sample. The chain is produced by taking an initial point  $x_0$  and repeatedly applying the following rule, where  $x_i$  is the current point:

- Draw a candidate step  $s$  from a proposal distribution  $J$ , which should be symmetric i.e.,  $J(-s) = J(s)$ .
- Calculate  $r = \min(\pi(x_i + s)/\pi(x_i), 1)$ .
- Let  $x_{i+1} = x_i + s$  with probability  $r$ , or  $x_i$  with probability  $1 - r$ .

An initial point estimate is produced before the chain starts, which is done so as to calculate the

approximate covariance matrix of the estimated parameters (as the inverse Hessian), and may also be used as the starting point of the chain.

The user can specify the starting point of the point estimate minimiser using `casal2 -i`. Don't start it too close to the actual estimate (either by using `casal2 -i`, or by changing the initial parameter values in input configuration file) as it takes a few iterations to form a reasonable approximation to the Hessian.

There is currently two options for the starting point of the Markov Chain:

- Start from the point estimate.
- Restart a chain given a covariance matrix and starting points (see section `arg1`)

The chain moves in natural space, i.e., no transformations are applied to the estimated parameters. The default proposal distribution is a multivariate t centred on the current point, with covariance matrix equal to a matrix based on the approximate covariance produced by the minimiser, times some stepsize factor. The following steps define the initial covariance matrix of the proposal distribution:

- The covariance matrix is taken as the inverse of the approximate Hessian from the quasi-Newton minimiser.
- The covariance matrix is modified so as to decrease all correlations greater than `@mcmc.max_correlation` down to `@mcmc.max_correlation`, and similarly to increase all correlations less than `-@mcmc.max_correlation` up to `-@mcmc.max_correlation` (the `@mcmc.max_correlation` parameter defaults to 0.8). This should help to avoid getting 'stuck' in a lower-dimensional subspace.
- The covariance matrix is then modified either by,
  - if `@mcmc.adjustment_method=covariance`: that if the variance of the  $i$ th parameter is non-zero and less than `@mcmc.min_difference` times the difference between the parameters' lower and upper bound, then the variance is changed, without changing the associated correlations, to  $k = \min\_diff(upper\_bound_i - lower\_bound_i)$ . This is done by setting

$$Cov(i, j)' = \sqrt{k} Cov(i, j) / sd(i)$$

for  $i \neq j$ , and  $var(i)' = k$

- if `@mcmc.adjustment_method=correlation`: that if the variance of the  $i$ th parameter is non-zero and less than `@mcmc.min_difference` times the difference between the parameters' lower and upper bound, then its variance is changed to  $k = \min\_diff(upper\_bound_i - lower\_bound_i)$ . This differs from (i) above in that the effect of this option is that it also modifies the resulting correlations between the  $i$ th parameter and all other parameters.

This allows each estimated parameter to move in the MCMC even if its variance is very small according to the inverse Hessian. In both cases, the `@mcmc.min_difference` parameter defaults to 0.0001.

- The `@mcmc.stepsize` (a scalar factor applied to the covariance matrix to improve the acceptance probability) is chosen by the user. The default is  $2.4d^{-0.5}$  where  $d$  is the number of estimated parameters, as recommended by Gelman et al. (Gelman et al., 1995). However, you may find that a smaller value may often be better.

The proposal distribution can also change adaptively during the chain, using two different mechanisms. Both are offered as means of improving the convergence properties of the chain. It is important to note that any adaptive behaviour must finish before the end of the burn-in period, i.e., the proposal distribution must be finalised before the kept portion of the chain starts. The adaptive mechanisms are as follows:

1. You can request that the stepsize change adaptively at one or more sample numbers (See next paragraph for details on the stepsize adaptation methods)
2. You can request that the entire covariance matrix change adaptively at one or more sample numbers. At each adaptation, the covariance matrix is replaced with an empirical covariance, derived from the MCMC chain. The idea here is that an empirical covariance is a better approximation to the proposal distribution than the inverse of the hessian matrix, and can improve convergence and mixing of your chain.

The two methods that you can choose to adapt the step size are `double_half` or `ratio`, this is done through the input parameter `adapt_stepsize_method`. The `double_half` method is used in CASAL and (See Gelman et al. (Gelman et al., 1995) for justification). The algorithm for `double_half` is, at each adaptation, the stepsize is doubled if the acceptance rate since the last adaptation is more than 0.5, or halved if the acceptance rate is less than 0.2. The `ratio` is taken from SPM. It adapts the current step size by, the acceptance rate since the last adaptation multiplied by 4.1667.

The stepsize parameter is now on a completely different scale, and must be reset. It is set to a user-specified value (which may or may not be the same as the initial stepsize). We recommend that some of the stepsize adaptations are set to occur after this, so that the stepsize can be readjusted to an appropriate value which gives good acceptance probabilities with the new matrix.

All modified versions of the covariance matrix are printed to the standard output, but only the initial covariance matrix (inverse Hessian) is saved to the objectives file. The number of covariance modifications by each iteration is recorded as a column on the objectives file.

The variance-covariance matrix of this sub-sample of chain is calculated. As above, correlations greater than `@mcmc.max_correlation` are reduced to `@mcmc.max_correlation`, correlations less than `@mcmc.max_correlation` are increased to `@mcmc.max_correlation`, and very small non-zero variances are increased (`@mcmc.covariance_adjustment` and `@mcmc.min_difference`). The result is the new variance-covariance matrix of the proposal distribution.

The procedure used to choose the sample of points is as follows. First, all points on the chain so far are taken. All points in an initial user-specified period are discarded. The assumption is that the chain will have started moving during this period - if this is incorrect and the chain has still not moved by the end of this period, it is a fatal error and CASAL2 stops. The remaining set of points must contain at least some user-specified number of transitions - if this is incorrect and the chain has not moved this often, it is again a fatal error. If this test is passed, the set of points is systematically sub-sampled down to 1000 points (it must be at least this long to start with).

The probability of acceptance for each jump is 0 if it would move out of the bounds, or 1 if it improves the posterior, or (new posterior/old posterior) otherwise. You can specify how often the position of the chain is recorded using the `keep` parameter. For example, with `keep 10`, only every 10th sample is recorded.

You have the option to specify that some of the estimated parameters are fixed during the MCMC. If the chain starts at the point estimate or at a random location, these fixed parameters are set to their values at the point estimate.

If you specify the start of the chain using `casal2 -i`, these fixed parameters are set to the values in the file.

Restarting a mcmc chain, in the case where computers get turned off and an mcmc execution is halted. There is the ability to restart it from where it finishes.

```
casal2 -m --resume --objective-file Objective_file_name --sample-file Sample_file_name
```

where `Objective_file_name` is the file name containing the objective report and `Sample_file_name` is the file name containing the sample report from a mcmc chain.

The posterior sample can be used for (projections (Section 4.6)) or simulations (Section 6.7) with the values supplied using `casal2 -i file`.

A multivariate t distribution is available as an alternative to the multivariate normal proposal distribution. If you request multivariate t proposals, you may want to change the degrees of freedom from the default of 4. As the degrees of freedom decrease, the t distribution becomes more heavy tailed. This may lead to better convergence properties.

Given a posterior (sub)sample, CASAL2 can calculate a list of output quantities for each sample point (see Section ?? specifically tabular report). These quantities can be dumped into a file (using `casal2 -r --tabular`) and read into an external software package where the posterior distributions can be plotted and/or summarised.

The posterior sample can also be used for projections (Section 4.6). The advantage of this is that the parameter uncertainty, as expressed in your posterior distribution, can be included into the risk estimates.

## 5.7. Priors

In a Bayesian analysis, you need to give a prior for every parameter that is being estimated. There are no default priors.

Note that when some of these priors are parameterised in terms of mean, c.v., and standard deviation, these refer to the parameters of the distribution before bounds are applied. The moments of the prior after the bounds are applied may differ.

CASAL2 has the following priors (expressed in terms of their contribution to the objective function):

1. Uniform

$$-\log(\pi(p)) = 0 \tag{5.2}$$

2. Uniform-log (i.e.,  $\log(p) \sim \text{uniform}$ )

$$-\log(\pi(p)) = \log(p) \tag{5.3}$$

3. Normal with mean  $\mu$  and c.v.  $c$

$$-\log(\pi(p)) = 0.5 \left( \frac{p - \mu}{c\mu} \right)^2 \tag{5.4}$$

4. Normal with mean  $\mu$  and standard deviation  $\sigma$

$$-\log(\pi(p)) = 0.5 \left( \frac{p - \mu}{\sigma} \right)^2 \quad (5.5)$$

5. Lognormal with mean  $\mu$  and c.v.  $c$

$$-\log(\pi(p)) = \log(p) + 0.5 \left( \frac{\log(p/\mu)}{s} + \frac{s}{2} \right)^2 \quad (5.6)$$

where  $s$  is the standard deviation of  $\log(p)$  and  $s = \sqrt{\log(1 + c^2)}$ .

6. Normal-log with  $\log(p)$  having mean  $m$  and standard deviation  $s$ ,

6. Beta with mean  $\mu$  and standard deviation  $\sigma$ , and range parameters  $A$  and  $B$

$$-\log(\pi(p)) = (1 - m) \log(p - A) + (1 - n) \log(B - p) \quad (5.7)$$

where  $v = \frac{\mu - A}{B - A}$ , and  $\tau = \frac{(\mu - A)(B - \mu)}{\sigma^2} - 1$  and then  $\mu = \tau v$  and  $n = \tau(1 - v)$ . Note that the beta prior is undefined when  $\tau \leq 0$ .

Vectors of parameters can be independently (but not necessarily identically) distributed according to any of the above forms, in which case the joint negative-log-prior for the vector is the sum of the negative-log-priors of the components. Values of each parameter need to be specified for each element of the vector.

In addition, for a vector  $p$  of  $n$  identically distributed parameters (for example, YCS) the following priors are allowed:

## 5.8. Penalties

Penalties are associated with processes and can be used to encourage or discourage parameter values or model outputs that are unlikely to be sensible, by adding a penalty to the objective function. For example, parameter estimates that do not allow a known mortality event to remove enough individuals from the population can be discouraged with an event mortality penalty. CASAL2 requires penalty functions for processes that move or shift a *number* of individuals between categories or from the partition.

For most penalties, you need to specify a multiplier, and the objective function is increased by this multiplier times the penalty value as described below. In some cases you will need to make the multiplier quite large to prohibit some model behaviour.

Currently, the penalties for the processes `@process[label].type=event_mortality`, `@process[label].type=tag_by_length` and `@process[label].type=category_transition` are the only penalties implemented.

For these processes, two types of penalty can be defined, natural scale (the default) and log scale. Both of these types add a penalty value of the squared difference between the observed value (i.e., the actual number of individuals to be removed in an event mortality process or the actual number

of individuals to shift in a category transition process), and the number that were moved (if less than or equal), times the penalty multiplier.

The natural scale penalty just uses at the squared difference on a natural scale, while the log scale penalty uses the squared difference of the logged values.

### 5.9. Additional Priors

Additional priors can be thought of as the inverse of penalties. They constrain parameters in certain spaces. The types of additional priors available in CASAL2 are `vector_smoothing` and `vector_averaging`, defined as,

1. `vector_averaging`

Applied to a vector parameter. Sum of squares of  $r$ th differences, optionally on a log scale. This encourages the vector to be like a polynomial of degree  $(r-1)$ . Note a range of the vector to be smoothed can be specified (and if not, the smoother is applied to the entire vector), but this must be specified by an index of the vector and must be between 1 and the length of the vector, inclusive.

2. `vector_smoothing`

Applied to a vector parameter. Square of  $(\text{mean}(\text{vector})-k)$ , or of  $(\text{mean}(\log(\text{vector}))-l)$ , or of  $(\log(\text{mean}(\text{vector})/m))$ . Encourages the vector to average arithmetically to  $k$  or  $m$ , or geometrically to  $\exp(l)$ . Typically used for YCS with  $k=1$  or  $m=1$  or  $l=0$ , to encourage the YCS to centre on 1. Optionally, you can choose to exclude indices outside a given set of bounds.



---

## 6. The observation section

### 6.1. Observations and likelihoods

Observations are typically supplied as observations at an instance in time, over some spatially aggregated area. Time series of observations can be supplied as separate observations for each year or point in time.

CASAL2 allows the following types of observations;

- Observations of proportions by age and length class within categories
- Observations of proportions between categories within age classes
- Tag recapture observation by length and age
- Proportions Migrating
- Relative and absolute abundance/biomass observations

The definitions for each type of observation are described below, including how the observed values should be supplied, how CASAL2 calculates the expected values, and the likelihoods that are available for each type of observation.

CASAL2 evaluates the observations at the end of a time-step (i.e., after all of the processes for that time-step have been applied). However, the observation can be applied to the abundance at the start of a time-step or part-way through a time-step by the use of the `proportion_time_step` subcommand.

By default (i.e., if `proportion_method = mean`), the partition at some point  $p$  during the time-step is then evaluated as the weighted sum between the start and end of the time-step, i.e. for any element  $i$  in the partition,  $n_i = (1 - p)n_i^{start} + pn_i^{end}$ . Note that it may not be sensible to use a value other than one, depending on the processes that happen during the time-step (for example, if the time-step contains an ageing process).

If the `proportion_method = difference`, then the observation is of the *difference* between the population state at the start of the time-step and the end. This can be used to generate expected values for observations of, for example removals due to a mortality event, by only having a single process in the time-step. In this case, the `proportion_time_step` is simply a multiplier of the population state.

### 6.2. Proportions-at-age observations

Proportions-at-age observations are observations of either the relative number of individuals at age or relative biomass at age, via some selectivity.

The observation is supplied for a given year and time-step, for some selected age classes of the population (i.e., for a range of ages multiplied by a selectivity), for categories aggregated over a set of spatial cells. Note that the categories defined in the observations must have an associated selectivity, defined by `selectivities`.

The age range must be ages defined in the partition (i.e., between `@model.min_age` and `@model.max_age` inclusive), but the upper end of the age range can optionally be a plus group — which must be either the same or less than the plus group defined for the partition.

Proportions-at-age observations can be supplied as;

1. a set of proportions for a single category,

2. a set of proportions for multiple categories, or
3. a set of proportions across aggregated categories.

For example, for a model with the two categories *male* and *female*, we might supply either (i) a set of proportions for a single category (i.e., males) within each age class; (ii) a set of proportions describing the proportions of individuals within each age class across multiple categories (i.e., males and females) simultaneously, or (iii) a set of proportions for the total number of individuals over the aggregated categories (i.e., males + females) combined, within each age class.

The way the categories of the observation are defined specifies which of these alternatives are used. It is also possible to have an observation with multiple and aggregated categories simultaneously.

### Proportions-at-age for a single category

This form of defining the observation is the simplest, and is used to model a set of proportions of a single category by age class. For example, to specify that the observations are of the proportions of male within each age class, then the subcommand `categories` for the `@observation[label].type=proportion_by_age` command is,

```
categories male
```

CASAL2 then expects that there will be a single vector of proportions supplied, with one proportion for each age class within the defined age range, and that these proportions sum to one.

For example, if the age range was 3 to 10, then 8 proportions should be supplied (one proportion for each of the ages 3, 4, 5, 6, 7, 8, 9, and 10). The expected values will be the expected proportions of males within each of these age classes (after ignoring any males aged less than 3 or older than 10), after applying a selectivity at the year and time-step specified. The supplied vector of proportions (i.e., in this example, the 8 proportions) must sum to one, which is evaluated with a default tolerance of 0.001.

```
@observation MyProportions
type proportions_at_age
...
categories male
min_age 1
max_age 5
years 1990
table obs
1990 0.01 0.09 0.20 0.30 0.40
end_table
...
```

### Proportions-at-age for multiple categories

This form of the observation extends the idea above for multiple categories. It is used to model a set of proportions over several categories by age class. For example, to specify that the observations are of the proportions of male or females within each age class, then the subcommand `categories` for the `@observation[label].type=proportion_by_age` command is,

```
categories male female
```

CASAL2 then expects that there will be a single vector of proportions supplied, with one proportion for each category and age class combination, and that these proportions sum to one.

For example, if there were two categories and the age range was 3 to 10, then 16 proportions should be supplied (one proportion for each of the the ages 3, 4, 5, 6, 7, 8, 9, and 10, for each category male and female). The expected values will be the expected proportions of males and within each of these age classes (after ignoring those aged less than 3 or older than 10), after applying a selectivity at the year and time-step specified. The supplied vector of proportions (i.e., in this example, the 16 proportions) must sum to one, which is evaluated with a default tolerance of 0.001.

For example,

```
@observation MyProportions
type proportions_at_age
...
categories male female
min_age 1
max_age 5
years 1990 1991
table obs
1990 0.01 0.05 0.10 0.20 0.20 0.01 0.05 0.15 0.20 0.03
1991 0.02 0.06 0.10 0.21 0.18 0.02 0.05 0.15 0.20 0.01
end_table
...
```

### Proportions-at-age across aggregated categories

This form of the observation extends the idea above, but allows categories to be aggregated before the proportions are calculated. It is used to model a set of proportions from several categories that have been combined by age class. To indicate that two (or more) categories are to be aggregated, separate them with a '+' symbol. For example, to specify that the observations are of the proportions of male and females combined within each age class, then the subcommand `categories` for the `@observation[label].type=proportion-by-age` command is,

```
categories male + female
```

CASAL2 then expects that there will be a single vector of proportions supplied, with one proportion for each age class, and that these proportions sum to one.

For example, if there were two categories and the age range was 3 to 10, then 8 proportions should be supplied (one proportion for each of the the ages 3, 4, 5, 6, 7, 8, 9, and 10, for the sum of males and females within each age class). The expected values will be the expected proportions of males + females within each of these age classes (after ignoring those aged less than 3 or older than 10), after applying a selectivity at the year and time-step specified. The supplied vector of proportions (i.e., in this example, the 16 proportions) must sum to one, which is evaluated with a default tolerance of 0.001.

For example, using the earlier spatial model with a categorical layer that has label Area, the observations for those spatial cells where the categorical layer has value A would be,

```
@observation MyProportions
type proportions_at_age
layer Area
...
years 1990 1991
categories male + female
```

```

min_age 1
max_age 5
table obs
1990 0.02 0.13 0.25 0.30 0.30
1991 0.02 0.06 0.18 0.35 0.39
end_table
...

```

The later form can then be extended to include multiple categories, or multiple aggregated categories. For example, to describe proportions for the three groups: immature males, mature males, and all females (immature and mature females added together) for ages 1–4, a total of 12 proportions are required

```

@observation MyProportions
type proportions_at_age
layer Area
...
categories male_immature male_mature female_immature + female_mature
min_age 1
max_age 4
years 1990
table obs
year 1990 0.05 0.15 0.15 0.05 0.02 0.03 0.08 0.04 0.05 0.15 0.15 0.08
end_table
...

```

### 6.2.1. Likelihoods for proportions-at-age observations

CASAL2 implements two likelihoods for proportions-at-age observations, the multinomial likelihood, dirichlet, and the lognormal likelihood.

#### The multinomial likelihood

For the observed proportions at age  $O_i$  for age classes  $i$ , with sample size  $N$ , and the expected proportions at the same age classes  $E_i$ , the negative log-likelihood is defined as;

$$-\log(L) = -\log(N!) + \sum_i \log((NO_i)!) - NO_i \log(Z(E_i, \delta)) \quad (6.1)$$

where  $\sum_i O_i = 1$  and  $\sum_i E_i = 1$ .  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.2)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

### The dirichlet likelihood

For the observed proportions at age  $O_i$  for age classes  $i$ , with sample size  $N$ , and the expected proportions at the same age classes  $E_i$ , the negative log-likelihood is defined as;

$$-\log(L) = -\log(\Gamma \sum_i (\alpha_i)) + \sum_i \log(\Gamma(\alpha_i)) - \sum_i (\alpha_i - 1) \log(Z(O_i, \delta)) \quad (6.3)$$

where  $\alpha_i = Z(N E_i, \delta)$ ,  $\sum_i O_i = 1$ , and  $\sum_i E_i = 1$ .  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.4)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

### The lognormal likelihood

For the observed proportions at age  $O_i$  for age classes  $i$ , with c.v.  $c_i$ , and the expected proportions at the same age classes  $E_i$ , the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \left( \log(\sigma_i) + 0.5 \left( \frac{\log(O_i / Z(E_i, \delta))}{\sigma_i} + 0.5 \sigma_i \right)^2 \right) \quad (6.5)$$

where

$$\sigma_i = \sqrt{\log(1 + c_i^2)} \quad (6.6)$$

and the  $c_i$ 's are the c.v.s for each age class  $i$ , and  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.7)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

## 6.3. Proportions-by-category observations

Proportions-by-category observations are observations of either the relative number of individuals between categories within age classes, or relative biomass between categories within age classes.

The observation is supplied for a given year and time-step, for some selected age classes of the population (i.e., for a range of ages multiplied by a selectivity), for categories aggregated over a set of spatial cells.

The age range must be ages defined in the partition (i.e., between `@model.min_age` and `@model.max_age` inclusive), but the upper end of the age range can optionally be a plus group — which may or may not be the same as the plus group defined for the partition.

Proportions-by-category observations can be supplied for any set of categories as a proportion of themselves and any set of additional categories. For example, for a model with the two categories *male* and *female*, we might supply observations of the proportions of males in the population at each age class. The subcommand `categories` defines the categories for the numerator in the calculation of the proportion, and the subcommand `categories2` supplies the additional categories to be used in the denominator of the calculation. In addition, each category must have an associated selectivity, defined by `selectivities` for the numerator categories and `selectivities2` for the additional categories used in the denominator, e.g.,

```
categories male
categories2 female
selectivities male-selectivity
selectivities2 female-selectivity
```

defines that the proportion of males in each age class as a proportion of males + females. CASAL2 then expects that there will be a vector of proportions supplied, with one proportion for each age class within the defined age range, i.e., if the age range was 3 to 10, then 8 proportions should be supplied (one proportion for each of the ages 3, 4, 5, 6, 7, 8, 9, and 10). The expected values will be the expected proportions of male to male + female within each of these age classes, after applying the selectivities at the year and time-step specified.

The observations must be supplied using all or some of the values defined by a categorical layer. CASAL2 calculates the expected values by summing over the ages (via the age range and selectivity) and categories for those spatial cells where the categorical layer has the same value as defined for each vector of observations i.e.,

```
@observation MyProportions
type proportions_by_category
years 1990 1991
...
categories male
categories2 female
min_age 1
max_age 5
table obs
1990 0.01 0.05 0.10 0.20 0.20
1991 0.02 0.06 0.10 0.21 0.18
end_table
...
```

### 6.3.1. Likelihoods for proportions-by-category observations

CASAL2 implements two likelihoods for proportions-by-category observations, the binomial likelihood, and the normal approximation to the binomial (binomial-approx).

#### The binomial likelihood

For observed proportions  $O_i$  for age class  $i$ , where  $E_i$  are the expected proportions for age class  $i$ , and  $N_i$  is the effective sample size for age class  $i$ , then the negative log-likelihood is defined as;

$$-\log(L) = -\sum_i [\log(N_i!) - \log((N_i(1 - O_i))!) - \log((N_i O_i)!) + N_i O_i \log(Z(E_i, \delta)) + N_i(1 - O_i) \log(Z(1 - E_i, \delta))] \quad (6.8)$$

where  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.9)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

### The normal approximation to the binomial likelihood

For observed proportions  $O_i$  for age class  $i$ , where  $E_i$  are the expected proportions for age class  $i$ , and  $N_i$  is the effective sample size for age class  $i$ , then the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \log \left( \sqrt{Z(E_i, \delta) Z(1 - E_i, \delta) / N_i} \right) + \frac{1}{2} \left( \frac{O_i - E_i}{\sqrt{Z(E_i, \delta) Z(1 - E_i, \delta) / N_i}} \right)^2 \quad (6.10)$$

where  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta / \delta), & \text{otherwise} \end{cases} \quad (6.11)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

## 6.4. Abundance or biomass observations

Abundance (or biomass) observations are observations of either a relative or absolute number (or biomass) of individuals from a set of categories after applying a selectivity. The observations classes are the same, except that a biomass observation will use the biomass as the observed (and expected) value (calculated from mean weight of individuals within each age and category) while an abundance observation is just the number of individuals.

Each observation is for a given year and time-step, for some selected age classes of the population (i.e., for a range of ages multiplied by a selectivity), for categories aggregated over a set of spatial cells. Further, you need to provide the label of the catchability coefficient  $q$ , which can either be estimated or fixed. For absolute abundance or absolute biomass observations, define a catchability where  $q = 1$ .

The observations can be supplied for any set of categories. For example, for a model with the two categories *male* and *female*, we might supply an observation of the total abundance/biomass (male + female) or just male abundance/biomass. The subcommand `categories` defines the categories used to aggregate the abundance/biomass. In addition, each category must have an associated selectivity, defined by `selectivities`. For example,

```
categories male
selectivities male-selectivity
```

defines an observation for males after applying the selectivity `male-selectivity`. CASAL2 then expects that there will be a single observation supplied. The expected values for the observations will be the expected abundance (or biomass) of males, after applying the selectivities, at the year and time-step specified.

The observations must be supplied using all or some of the values of defined by a categorical layer. CASAL2 calculates the expected values by summing over the defined ages (via the age range and selectivity) and categories for those spatial cells where the categorical layer has the same value as defined for each vector of observations i.e.,

```
@observation MyAbundance
type abundance
years 1999
...
categories male
obs 1000
...
```

Or, for both  $A$  and  $B$  as,

```
@observation MyAbundance
type abundance
years 1990 1991
...
categories male
table obs
1990 1000
1991 1200
end_table
...
```

To supply an observation for individual spatial cells, then you will need to define a categorical layer with a single, unique value for each spatial cell.

Note that, to define a biomass observation instead of an abundance observation, use

```
@observation MyBiomass
type biomass
...
```

#### 6.4.1. Likelihoods for abundance observations

##### The lognormal likelihood

For observations  $O_i$ , c.v.  $c_i$ , and expected values  $qE_i$ , the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \left( \log(\sigma_i) + 0.5 \left( \frac{\log(O_i/qZ(E_i, \delta))}{\sigma_i} + 0.5\sigma_i \right)^2 \right) \quad (6.12)$$

where

$$\sigma_i = \sqrt{\log(1 + c_i^2)} \quad (6.13)$$

and  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta/(2 - \theta/\delta), & \text{otherwise} \end{cases} \quad (6.14)$$



The default value of  $\delta$  is  $1 \times 10^{-11}$ .

### The normal likelihood

For observations  $O_i$ , c.v.  $c_i$ , and expected values  $qE_i$ , the negative log-likelihood is defined as;

$$-\log(L) = \sum_i \left( \log(c_i E_i) + 0.5 \left( \frac{O_i - E_i}{Z(c_i E_i, \delta)} \right)^2 \right) \quad (6.15)$$

and  $Z(\theta, \delta)$  is a robustifying function to prevent division by zero errors, with parameter  $\delta > 0$ .  $Z(\theta, \delta)$  is defined as,

$$Z(\theta, \delta) = \begin{cases} \theta, & \text{where } \theta \geq r \\ \delta / (2 - \theta/\delta), & \text{otherwise} \end{cases} \quad (6.16)$$

The default value of  $\delta$  is  $1 \times 10^{-11}$ .

## 6.5. Process error

Additional ‘process error’ can be defined for each set of observations. Additional process error has the effect of increasing the observation error in the data, and hence of decreasing the relative weight given to the data in the fitting process.

For observations where the likelihood is parameterised by the c.v., you can specify the process error for a given set of observations as a c.v., in which case all the c.v.s  $c_i$  are changed to

$$c'_i = \sqrt{c_i^2 + c_{process\_error}^2} \quad (6.17)$$

Note that  $c_{process\_error} \geq 0$ , and that  $c_{process\_error} = 0$  is equivalent to no process error.

Similarly, if the likelihood is parameterised by the effective sample size  $N$ ,

$$N'_i = \frac{1}{1/N_i + 1/N_{process\_error}} \quad (6.18)$$

Note that this requires that  $N_{process\_error} > 0$ , but we allow the special case of  $N_{process\_error} = 0$ , and define  $N_{process\_error} = 0$  as no process error (i.e., defined to be equivalent to  $N_{process\_error} = \infty$ ).

For both the c.v. and  $N$  process errors, the process error has more effect on small errors than on large ones. Be clear that a large value for the  $N$  process error means a small process error.

## 6.6. Ageing error

CASAL2 can apply ageing error age frequency observations. Ageing error is applied to the expected values for proportions-at-age observations. The ageing error is applied as a misclassification matrix, which has the effect of ‘smearing’ the age frequencies. These are used in calculating the fits to the observed values, and hence the contribution to the total objective function.

Ageing error is optional, and if it is used, it may be omitted for any individual time series. Different ageing error models may be applied for different observation commands. See Section 7.12 for reporting the misclassification matrix.

The ageing error models implemented are,

1. None: The default model is to apply no ageing error.
2. Off by one: Proportion  $p_1$  of individuals of each age  $a$  are misclassified as age  $a - 1$  and proportion  $p_2$  are misclassified as age  $a + 1$ . Individuals of age  $a < k$  are not misclassified. If there is no plus group in the population model, then proportion  $p_2$  of the oldest age class will 'fall off the edge' and disappear.
3. Normal: Individuals of age  $a$  are classified as ages which are normally distributed with mean  $a$  and constant c.v.  $c$ . As above, if there is no plus group in the population model, some individuals of the older age classes may disappear. If  $c$  is high enough, some of the younger age classes may 'fall off the other edge'. Individuals of age  $a < k$  are not misclassified.

Note that the expected values (fits) reported by CASAL2 for observations with ageing error will have had the ageing error applied.

### 6.7. Simulating observations

CASAL2 can generate simulated observations for a given model with given parameter values (using `casal2 -s 1`). Simulated observations are randomly distributed values, generated according to the error assumptions defined for each observation, around fits calculated from one or more sets of the 'true' parameter values. Simulating from a set of parameters can be used to generate observations from an operating model or as a form of parametric bootstrap.

The procedure CASAL2 uses for simulating observations is to first run using the 'true' parameter values and generate the expected values. Then, if a set of observations uses ageing error, ageing error is applied. Finally a random value for each observed value is generated based on (i) the expected values, (ii) the type of likelihood specified, and (iii) the variability parameters (e.g., `error_value` and `process_error`).

Methods for generating the random error, and hence simulated values, depend on the specific likelihood type of each observation.

1. Normal likelihood parameterised by c.v.: Let  $E_i$  be the fitted value for observation  $i$ , and  $c_i$  be the corresponding c.v. (adjusted by the process error if applicable). Each simulated observation value  $S_i$  is generated as an independent normal deviate with mean  $E_i$  and standard deviation  $E_i c_i$ .
2. Log-normal likelihood: Let  $E_i$  be the fitted value for observation  $i$  and  $c_i$  be the corresponding c.v. (adjusted by the process error if applicable). Each simulated observation value  $S_i$  is generated as an independent lognormal deviate with mean and standard deviation (on the natural scale, not the log-scale) of  $E_i$  and  $E_i c_i$  respectively. The robustification parameter  $\delta$  is ignored.
3. Multinomial likelihood: Let  $E_i$  be the fitted value for observation  $i$ , for  $i$  between 1 and  $n$ , and let  $N$  be the sample size (adjusted by process error if applicable, and then rounded up to the next whole number). The robustification parameter  $\delta$  is ignored. Then,
  - a) A sample of  $N$  values from 1 to  $n$  is generated using the multinomial distribution, using sample probabilities proportional to the values of  $E_i$ .
  - b) Each simulated observation value  $S_i$  is calculated as the proportion of the  $N$  sampled values equalling  $i$
  - c) The simulated observation values  $S_i$  are then rescaled so that their sum is equal to 1
4. Binomial and the normal approximation to the binomial likelihoods: Let  $E_i$  be the fitted value for observation  $i$ , for  $i$  between 1 and  $n$ , and  $N_i$  the corresponding equivalent sample size (adjusted by process error if applicable, and then rounded up to the next whole number). The robustification parameter  $\delta$  is ignored. Then,
  - a) A sample of  $N_i$  independent binary variates is generated, equalling 1 with probability  $E_i$
  - b) The simulated observation value  $S_i$  is calculated as the sum of these binary variates divided by  $N_i$

Note that CASAL2 will report simulated observations using the usual observation report (`@report[label].type=observation`). The report `@report[label].type=simulated_observation` will generate simulated observations in a form suitable for use as input within a CASAL2 input configuration file. See Section ?? for more detail.

## 6.8. Pseudo-observations

CASAL2 can generate expected values for observations without them contributing to the total objective function. These are called pseudo-observations, and can be used to either generate the expected values from CASAL2 for reporting or diagnostic purposes. To define an observation as a pseudo-observation, use the command `@observation[label].likelihood=none`. Any observation type can be used as a pseudo-observation. CASAL2 can also generate simulated observations from pseudo-observations. Note that;

- Output will only be generated if a report command `@report[label].type=observation` is specified.
- The observed values should be supplied (even if they are ‘dummy’ observation). These will be processed by CASAL2 as if they were actual observation values, and must conform to the validations carried out for the other types of likelihood.
- The subcommands `likelihood`, `obs`, `error_value` and `process_error` have no effect when generating the expected values for the pseudo-observation.
- When simulating observations, CASAL2 needs the subcommand `simulation_likelihood` to tell it what sort of likelihood to use. In this case, the `obs`, `error_value` and `process_error` are used to determine the appropriate terms to use for the likelihood when simulating.



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## 7. The report section

The report section specifies the printouts and other outputs from the model. CASAL2 does not, in general, produce any output unless requested by a valid `@report` block.

Reports from CASAL2 can be defined to print partition and states objects at a particular point in time, observation summaries, estimated parameters and objective function values. See below for a more extensive list, and an example of an observation report.

```
@report observation_age ## label of report
type observation ## Type of report
observation age_1990 ## label corresponding to an @observation report, shown below

@observation age_1990
type proportion_at_age
year 1990
plus_group
etc ...
```

Reports from CASAL2 all conform to a standard style (with one exception — the `output_parameters` report, see below). The standard style is that reports are prefixed with an aster-ix followed by a user-defined label and type of report in brackets (e.g., `*label (type)`), with the report ending with the line `*end`. For example,

```
*My_report (type)
...
*end
```

This syntax should make it easier for external packages to be configured to read CASAL2 output. The `extract` functions in the **R** CASAL2 package uses this information to identify and read CASAL2 output within an **R** environment.

Note that the `output_parameters` report does not print either a header or `*end` at the end of the report. This is as the `output_parameters` report is designed to provide a single line (or multi-line for more than one set) vector of the estimated parameter values, suitable for reading by CASAL2 (with the command `casal2 -i`). This is a specialised report for `casal2 -o filename` command. For estimate values in standard output users are recommended to use `type=estimate_value`.

Reports can be defined in an `@report` but may not be generated. For example printing the partition for a year and/or time-step that does not exist or reporting the covariance matrix when not estimating. Certain reports are associated with certain CASAL2 run modes. Such reports are ignored by CASAL2 and the program will not generate any output for these reports — although they must still conform to CASAL2s syntax requirements.

Not all reports will be generated in all run modes. Some reports are only available in some run modes. For example, when simulating, only simulation reports will be output.

### 7.1. Print the partition at the end of an initialisation

Print the partition following an initialisation phase. This prints out, the numbers of individuals in each age class and category in the partition following an initialisation phase. This report will print out in the following runmodes `-r`, `-e`, `-f`.

### 7.2. Print the partition

Print the partition for a given year or given years and time-step. This prints out, the numbers of individuals in each age class and category in the partition for each year. Note that this report is evaluated at the end of the time-step in the given year(s). This report will print out in the following runmodes `-r`, `-e`, `-f`.

### 7.3. Print the age length and length weight values

Print the length and weight for an age of the partition for a given year or given years and time-step. This prints out, the length and weight value for each age class and category in the partition for each year and time step. Note that this report is evaluated at the end of the time-step in the given year(s). This report will print out in the following runmodes `-r`, `-e`, `-f`.

```
@report length_weight_at_age
type partition_mean_weight
time_step step2
years 1900:2013
```

### 7.4. Print a process summary

Print a summary of a process. Depending on the process, different summaries are produced. These typically detail the type of process, its parameters and other options, and any associated details. This report will print out in the following runmodes `-r`, `-e`, `-f`.

### 7.5. Print derived quantities

Print out the description of the derived quantity, and the values of the derived quantity as recorded in the model state, for each year of the model. and for all years in the initialisation phases. This report will print out in the following runmodes `-r`, `-e`, `-f`.

### 7.6. Print the estimated parameters

Print a summary of the estimated parameters using the following type `estimate_summary`, including the parameter name, lower and upper bounds, the label of the prior, and its value. This report will print out in the following runmodes `-r`, `-e`.

### 7.7. Print the estimated parameters in a vector format

Print the estimated parameter values out as a vector. The `estimate_values` report prints the name of the parameter, followed by the value of that run. This report will print out in the following runmodes `-r`, `-e`.

### 7.8. Print the objective function

Print the total objective function value, and the value of all observations, the values of all priors, and the value of any penalties that have been incurred in the model. Note that if an individual model run does not incur a penalty, then the penalty will not be reported. This report will print out in the following runmodes `-r`, `-e`, `-f`.

### 7.9. Print the covariance matrix

Print the Hessian and covariance matrices if estimating and if the covariance has been requested by `@minimiser[label].covariance=true`.

### 7.10. Print observations, fits, and residuals

Prints out for each category or combination of categories, expected values as calculated by the model, residuals (observed – expected), the error value, process error, and the total error (i.e., the error value as

modified by any additional process error), and the contribution to the total objective function of that individual point in the observation.

Note that constants in likelihoods are often ignored in the objective function score of individual points. Hence, the total score from an observation equals the contribution of the objective function scores from each individual point plus a constant term (if applicable). In likelihoods without a constant term, then the total score from an observation will equal the contribution of the objective function scores from each individual point.

If simulating, then the contribution to the objective function of each observation is reported as zero.

### **7.11. Print simulated observations**

Prints out a complete observation definition (i.e., in the form defined by `@report[label].type=observation`), but with observed values replaced by randomly generated simulated values. The output is in a form suitable for use within a CASAL2 input configuration file, reproducing the command and subcommands from the input configuration file. This report will print out in the following runmodes `-s`.

### **7.12. Print the ageing error misclassification matrix**

Prints out the ageing error misclassification matrix used to offset observations within during model the model fitting procedure.

### **7.13. Print selectivities**

Prints the values of a selectivity for each age in the partition, for a given year and at then end of a given time-step.

### **7.14. Print the random number seed**

Prints the random number seed used by CASAL2 to generate the random number sequence. Future runs made with the same random number seed and the same model will produce identical outputs.

### **7.15. Print the results of an MCMC**

Print the MCMC samples, objective function values, and proposal covariance matrix following an MCMC. This report will print out in the following runmode `-m`.

### **7.16. Print the MCMC samples as they are calculated**

Print the MCMC samples for each new *i*th sample as they are calculated while doing an MCMC. The output file will be updated with each new sample as it is calculated by CASAL2. This report will print out in the following runmodes `-m`.

### **7.17. Print the MCMC objective function values as they are calculated**

Print the MCMC objective function values (along with the proposal covariance matrix) for each new *i*th sample as they are calculated while doing an MCMC. The output file will be updated with each new set of objective function values as it is calculated by CASAL2. This report will print out in the following runmodes `-m`.

### 7.18. Print time varying parameters

Print all `@time_varying` blocks with the values and years that they were implemented in. This report will print out in the following runmodes `-r`, `-e`, `-m`.

```
@report time_varying_parameters
type time_varying
```

### 7.19. Tabular reporting

An alternative reporting framework to the standard output is the tabular reporting. Tabular reporting is used with multiline `-i` input files (like the MCMC sample or `-o` outputs). Tabular reports will print out a row that will correspond with each row of the `-i` input files. Tabular reporting is invoked at the command line using the following command `casal2 -r --tabular -i file_name`. Currently derived quantities and `estimate_values` are the only report types that are within this framework. For each input file the output will begin with the names of each column followed by a multiline report ending with the `*end` syntax. These tables can be easily read into **R** using the `CASAL2` package and for the example of MCMC multi-line files posteriors of derived quantities can be plotted.



---

## 8. Population command and subcommand syntax

For ease of reading CASAL2 files in text editors, there exists a syntax highlighter `CASAL2.syn`

### 8.1. Model structure

`@model label` Define an object type Model

`age_plus` Define the oldest age as a plus group

Type: boolean

Default: false

Value: true, false

`final_year` Define the final year of the model, excluding years in the projection period

Type: non-negative integer

Default: No Default

Value: Defines the last year of the model, i.e., the model is run from `start_year` to `final_year`

`initialisation_phases` Define the labels of the phases of the initialisation

Type: string vector

Default: true

Value: A list of valid labels defined by `@initialisation_phase`

`label`

Type: string

Default: No Default

`length_bins`

Type: constant vector

Default: true

`max_age` Maximum age of individuals in the population

Type: non-negative integer

Default: 0

Value:  $0 \leq \text{age}_{\min} \leq \text{age}_{\max}$

`min_age` Minimum age of individuals in the population

Type: non-negative integer

Default: 0

Value:  $0 \leq \text{age}_{\min} \leq \text{age}_{\max}$

`projection_final_year` Define the final year of the model in projection mode

Type: non-negative integer

Default: 0

Value: Defines the last year of the projection period, i.e., the projection period runs from `final_year+1` to `projection_final_year`. For the default, 0, no projections are run.

`start_year`      Define the first year of the model, immediately following initialisation

Type: non-negative integer

Default: No Default

Value: Defines the first year of the model,  $\geq 1$ , e.g. 1990

`time_steps`      Define the labels of the time steps, in the order that they are applied, to form the annual cycle

Type: string vector

Default: No Default

Value: A list of valid labels defined by `@time_step`

`type`      Type of model (the partition structure). Either age, length or hybrid

Type: string

Default: age

## 8.2. Initialisation

**`@initialisation_phase label`**      Define an object type Initialisation.Phase

`label`      Label

Type: string

Default: No Default

`type`      Type

Type: string

Default: iterative

### 8.2.1. `@initialisation_phase[label].type=cinitial`

`categories`      List of categories to use

Type: string vector

Default: No Default

### 8.2.2. `@initialisation_phase[label].type=derived`

`casal.initialisation.switch`      Reset the partition after running an extra annual cycle to take on equilibrium SSB's. Warning should only be set to true if comparing with previous CASAL models

Type: boolean

Default: false

`exclude_processes`      The processes to exclude from all time steps

Type: string vector

Default: true

`insert_processes`      The processes to insert in to target time steps  
Type: string vector  
Default: true

### 8.2.3. `@initialisation_phase[label].type=iterative`

`convergence_years`      The years to test for convergence  
Type: non-negative integer vector  
Default: true

`exclude_processes`      The processes to exclude from all time steps  
Type: string vector  
Default: true

`insert_processes`      The processes to insert in to target time steps  
Type: string vector  
Default: true

`lambda`      Lambda  
Type: constant  
Default: Double(0.0)

`years`      The number of iterations to execute this phase for  
Type: non-negative integer  
Default: No Default

### 8.2.4. `@initialisation_phase[label].type=state_category_by_age`

`categories`      List of categories to use  
Type: string vector  
Default: No Default

`max_age`      Maximum age to use for this process  
Type: non-negative integer  
Default: No Default

`min_age`      Minimum age to use for this process  
Type: non-negative integer  
Default: No Default

### 8.3. Categories

**@categories** *label* Define an object type Categories

*age\_lengths* The labels of *age\_length* objects that are assigned to categories

Type: string vector

Default: true

*format* The format that the category names should adhere too

Type: string

Default: No Default

*names* The names of the categories to be used in the model

Type: string vector

Default: No Default

*years* The years that individual categories will be active for. This overrides the model values

Type: string vector

Default: true

### 8.4. Time-steps

**@time\_step** *label* Define an object type Time\_Step

*label* Label

Type: string

Default: No Default

*processes* Processes

Type: string vector

Default: No Default

*type*

Type: string

Default: No Default

### 8.5. Processes

**@process** *label* Define an object type Process

*print\_report* Generate parameter report

Type: boolean

Default: false

*label* Label

Type: string  
Default: No Default

type      Type  
Type: string  
Default: ""

### 8.5.1. @process[label].type=ageing

categories      Categories  
Type: string vector  
Default: No Default

print\_report      Generate parameter report  
Type: boolean  
Default: false

### 8.5.2. @process[label].type=growth

print\_report      Generate parameter report  
Type: boolean  
Default: false

### 8.5.3. @process[label].type=maturation

print\_report      Generate parameter report  
Type: boolean  
Default: false

from      List of categories to mature from  
Type: string vector  
Default: No Default

rates      The rates to mature for each year  
Type: constant vector  
Default: No Default

selectivities      List of selectivities to use for maturation  
Type: string vector  
Default: No Default

to      List of categories to mature too

Type: string vector  
Default: No Default

years      The years to be associated with rates  
Type: non-negative integer vector  
Default: No Default

#### **8.5.4. @process[label].type=mortality\_constant\_rate**

categories      List of categories  
Type: string vector  
Default: No Default

print\_report      Generate parameter report  
Type: boolean  
Default: false

m      Mortality rates  
Type: constant vector  
Default: No Default

time\_step\_ratio      Time step ratios for M  
Type: constant vector  
Default: true

selectivities      Selectivities  
Type: string vector  
Default: No Default

#### **8.5.5. @process[label].type=mortality\_event**

catches      Catches  
Type: constant vector  
Default: No Default

categories      Categories  
Type: string vector  
Default: No Default

print\_report      Generate parameter report  
Type: boolean  
Default: false

penalty      Penalty label

Type: string  
Default: ""

selectivities      List of selectivities  
Type: string vector  
Default: No Default

u\_max      U Max  
Type: constant  
Default: 0.99

years      Years  
Type: non-negative integer vector  
Default: No Default

### 8.5.6. @process[label].type=mortality\_event\_biomass

catches      Catches for each year  
Type: constant vector  
Default: No Default

categories      Category labels  
Type: string vector  
Default: No Default

print\_report      Generate parameter report  
Type: boolean  
Default: false

penalty      Penalty label  
Type: string  
Default: ""

selectivities      Selectivity labels  
Type: string vector  
Default: No Default

u\_max      U Max  
Type: constant  
Default: 0.99

units      Unit of weight that the Catches table are expressed in  
Type: string  
Default: No Default

years      Years to apply mortality  
Type: non-negative integer vector  
Default: No Default

### 8.5.7. `@process[label].type=mortality holling rate`

a      parameter a  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (inclusive)

b      parameter b  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (inclusive)

print\_report      Generate parameter report  
Type: boolean  
Default: false

is\_abundance      Is vulnerable amount for prey and predator in Abundance (TRUE) or biomass (FALSE)  
Type: boolean  
Default: true

penalty      Label of penalty to be applied  
Type: string  
Default: ""

predator\_categories      Predator Categories labels  
Type: string vector  
Default: No Default

predator\_selectivities      Selectivities for predator categories  
Type: string vector  
Default: No Default

prey\_categories      Prey Categories labels  
Type: string vector  
Default: No Default

prey\_selectivities      Selectivities for prey categories  
Type: string vector  
Default: No Default



u\_max      Umax

Type: constant

Default: No Default

Lower Bound: 0.0 (inclusive)

Upper Bound: 1.0 (inclusive)

x      This parameter controls the type of functional form, Holling function type 2 (x=2) or 3 (x=3), or generalised (Michaelis Menten)

Type: constant

Default: No Default

Lower Bound: 1.0 (inclusive)

years      Year to execute in

Type: non-negative integer vector

Default: No Default

### 8.5.8. @process[label].type=mortality\_instantaneous

categories      Categories for natural mortality

Type: string vector

Default: No Default

print\_report      Generate parameter report

Type: boolean

Default: false

m      Mortality rates

Type: constant vector

Default: No Default

Lower Bound: 0.0 (inclusive)

Upper Bound: 1.0 (inclusive)

selectivities      Selectivities for Natural Mortality

Type: string vector

Default: No Default

time\_step\_ratio      Time step ratios for M

Type: constant vector

Default: true

units      Unit of weight that the Catches table are expressed in

Type: string

Default: No Default

### 8.5.9. @process[label].type=mortality\_prey\_suitability

consumption\_rate      Predator consumption rate

Type: constant

Default: No Default

Lower Bound: 0.0 (inclusive)

Upper Bound: 1.0 (inclusive)

print\_report      Generate parameter report

Type: boolean

Default: false

electivities      Prey Electivities

Type: constant vector

Default: No Default

Lower Bound: 0.0 (inclusive)

Upper Bound: 1.0 (inclusive)

penalty      Label of penalty to be applied

Type: string

Default: ""

predator\_categories      Predator Categories labels

Type: string vector

Default: No Default

predator\_selectivities      Selectivities for predator categories

Type: string vector

Default: No Default

prey\_categories      Prey Categories labels

Type: string vector

Default: No Default

prey\_selectivities      Selectivities for prey categories

Type: string vector

Default: No Default

u\_max      Umax

Type: constant

Default: No Default

Lower Bound: 0.0 (inclusive)

Upper Bound: 1.0 (inclusive)

years      Year that process occurs

Type: non-negative integer vector

Default: No Default

#### 8.5.10. `@process[label].type=nop`

`print_report`      Generate parameter report

Type: boolean

Default: false

#### 8.5.11. `@process[label].type=recruitment_beverton_holt`

`age`      Age to recruit at

Type: non-negative integer

Default: true

`b0`      B0

Type: constant

Default: false

`units`      Units of B0, if initialising model using B0

Type: string

Default: ""

`categories`      Category labels

Type: string vector

Default: No Default

`print_report`      Generate parameter report

Type: boolean

Default: false

`b0_initialisation_phase`      Initialisation phase Label that b0 is from

Type: string

Default: ""

`prior_standardised_ycs`      Priors for year class strength on ycs values (not standardised ycs values)

Type: boolean

Default: true

`proportions`      Proportions

Type: constant vector

Default: No Default

r0      R0

Type: constant

Default: false

ssb      SSB Label (derived quantity)

Type: string

Default: No Default

ssb\_offset      Spawning biomass year offset

Type: integer

Default: false

standardise\_ycs\_years      Years that are included for year class standardisation

Type: non-negative integer vector

Default: true

steepness      Steepness

Type: constant

Default: 1.0

ycs\_values      YCS Values

Type: constant vector

Default: No Default

#### **8.5.12. @process[label].type=recruitment\_constant**

age      Age

Type: non-negative integer

Default: No Default

categories      Categories

Type: string vector

Default: No Default

print\_report      Generate parameter report

Type: boolean

Default: false

proportions      Proportions

Type: constant vector

Default: true

r0      R0

Type: constant  
Default: No Default  
Lower Bound: 0.0 (exclusive)

### 8.5.13. `@process[label].type=tag_by_age`

`print_report`      Generate parameter report  
Type: boolean  
Default: false

`from`      Categories to transition from  
Type: string vector  
Default: No Default

`initial_mortality`  
Type: constant  
Default: Double(0)

`initial_mortality_selectivity`  
Type: string  
Default: ""

`loss_rate`  
Type: constant vector  
Default: No Default

`loss_rate_selectivities`  
Type: string vector  
Default: true

`max_age`      Maximum age to transition  
Type: non-negative integer  
Default: No Default

`min_age`      Minimum age to transition  
Type: non-negative integer  
Default: No Default

`n`  
Type: constant vector  
Default: true

`penalty`      Penalty label  
Type: string  
Default: ""

`selectivities`

Type: string vector

Default: No Default

`to` Categories to transition to

Type: string vector

Default: No Default

`u_max` U Max

Type: constant

Default: 0.99

`years` Years to execute the transition in

Type: non-negative integer vector

Default: No Default

#### **8.5.14. @process[label].type=tag\_by\_length**

`print_report` Generate parameter report

Type: boolean

Default: false

`from` Categories to transition from

Type: string vector

Default: No Default

`initial_mortality`

Type: constant

Default: Double(0)

`initial_mortality_selectivity`

Type: string

Default: ""

`maximum_length` The upper length when there is no plus group

Type: constant

Default: Double(0)

`n`

Type: constant vector

Default: true

`penalty` Penalty label

Type: string  
Default: ""

`plus_group`      Use plus group for last length bin  
Type: boolean  
Default: false

`selectivities`  
Type: string vector  
Default: No Default

`to`      Categories to transition to  
Type: string vector  
Default: No Default

`u_max`      U Max  
Type: constant  
Default: 0.99

`years`      Years to execute the transition in  
Type: non-negative integer vector  
Default: No Default

### 8.5.15. `@process[label].type=tag_loss`

`categories`      List of categories  
Type: string vector  
Default: No Default

`print_report`      Generate parameter report  
Type: boolean  
Default: false

`time_step_ratio`      Time step ratios for Tag Loss  
Type: constant vector  
Default: true

`selectivities`      Selectivities  
Type: string vector  
Default: No Default

`tag_loss_rate`      Tag Loss rates  
Type: constant vector  
Default: No Default

tag\_loss\_type    Type of tag loss  
Type: string  
Default: No Default

year    The year the first tagging release process was executed  
Type: non-negative integer  
Default: No Default

#### **8.5.16. @process[label].type=transition\_category**

print\_report    Generate parameter report  
Type: boolean  
Default: false

from    From  
Type: string vector  
Default: No Default

proportions    Proportions  
Type: constant vector  
Default: No Default

selectivities    Selectivity names  
Type: string vector  
Default: No Default

to    To  
Type: string vector  
Default: No Default

#### **8.5.17. @process[label].type=transition\_category\_by\_age**

print\_report    Generate parameter report  
Type: boolean  
Default: false

from    Categories to transition from  
Type: string vector  
Default: No Default

max\_age    Maximum age to transition  
Type: non-negative integer  
Default: No Default



`min_age` Minimum age to transition  
Type: non-negative integer  
Default: No Default

`penalty` Penalty label  
Type: string  
Default: ""

`to` Categories to transition to  
Type: string vector  
Default: No Default

`u_max` U Max  
Type: constant  
Default: 0.99

`years` Years to execute the transition in  
Type: non-negative integer vector  
Default: No Default

## 8.6. Time varying parameters

**@time\_varying** *label* Define an object type Time\_Varying

`label` Label  
Type: string  
Default: No Default

`parameter` Parameter to vary  
Type: string  
Default: No Default

`type` Type  
Type: string  
Default: ""

`years` Years to recalculate the values  
Type: non-negative integer vector  
Default: No Default

### 8.6.1. @time\_varying[label].type=annual\_shift

`a`  
Type: constant  
Default: No Default

b

Type: constant

Default: No Default

c

Type: constant

Default: No Default

parameter      Parameter to vary

Type: string

Default: No Default

scaling\_years

Type: non-negative integer vector

Default: true

values

Type: constant vector

Default: No Default

years      Years to recalculate the values

Type: non-negative integer vector

Default: No Default

### **8.6.2. @time\_varying[label].type=constant**

parameter      Parameter to vary

Type: string

Default: No Default

value      Value to assign to estimable

Type: constant vector

Default: No Default

years      Years to recalculate the values

Type: non-negative integer vector

Default: No Default

### **8.6.3. @time\_varying[label].type=exogenous**

a      Shift parameter

Type: constant

Default: No Default

exogeneous\_variable      Values of exogeneous variable for each year  
Type: constant vector  
Default: No Default

parameter      Parameter to vary  
Type: string  
Default: No Default

years      Years to recalculate the values  
Type: non-negative integer vector  
Default: No Default

#### **8.6.4. @time\_varying[label].type=linear**

parameter      Parameter to vary  
Type: string  
Default: No Default

slope      The slope of the linear trend (additive unit per year)  
Type: constant  
Default: 0

years      Years to recalculate the values  
Type: non-negative integer vector  
Default: No Default

#### **8.6.5. @time\_varying[label].type=random\_walk**

distribution      distribution  
Type: string  
Default: normal

mean      Mean  
Type: constant  
Default: 0

parameter      Parameter to vary  
Type: string  
Default: No Default

sigma      Standard deviation  
Type: constant  
Default: 1

years      Years to recalculate the values  
Type: non-negative integer vector  
Default: No Default

## 8.7. Derived quantities

**@derived\_quantity** *label*      Define an object type Derived\_Quantity

categories      The list of categories to use when calculating the derived quantity  
Type: string vector  
Default: No Default

label      Label  
Type: string  
Default: No Default

time\_step\_proportion\_method  
Type: string  
Default: weighted\_sum  
Allowed Values: weighted\_sum, weighted\_product

selectivities      The list of selectivities to use when calculating the derived quantity. 1 per category  
Type: string vector  
Default: No Default

time\_step      The time step to calculate the derived quantity after  
Type: string  
Default: No Default

time\_step\_proportion  
Type: constant  
Default: Double(1.0)

type      Type  
Type: string  
Default: No Default

### 8.7.1. @derived\_\_quantity[label].type=abundance

categories      The list of categories to use when calculating the derived quantity  
Type: string vector  
Default: No Default

time\_step\_proportion\_method

Type: string

Default: weighted\_sum

Allowed Values: weighted\_sum, weighted\_product

selectivities      The list of selectivities to use when calculating the derived quantity. 1 per category

Type: string vector

Default: No Default

time\_step      The time step to calculate the derived quantity after

Type: string

Default: No Default

time\_step\_proportion

Type: constant

Default: Double(1.0)

### 8.7.2. @derived\_quantity[label].type=biomass

categories      The list of categories to use when calculating the derived quantity

Type: string vector

Default: No Default

time\_step\_proportion\_method

Type: string

Default: weighted\_sum

Allowed Values: weighted\_sum, weighted\_product

selectivities      The list of selectivities to use when calculating the derived quantity. 1 per category

Type: string vector

Default: No Default

time\_step      The time step to calculate the derived quantity after

Type: string

Default: No Default

time\_step\_proportion

Type: constant

Default: Double(1.0)

## 8.8. Age-length relationship

**@age\_length** *label* Define an object type Age.Length

**casal\_switch** A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm

Type: boolean

Default: false

**cv\_first** CV for the first age class

Type: constant

Default: Double(0.0)

Lower Bound: 0.0 (inclusive)

**cv\_last** CV for last age class

Type: constant

Default: Double(0.0)

Lower Bound: 0.0 (inclusive)

**distribution** The assumed distribution for the growth curve

Type: string

Default: normal

**label** Label

Type: string

Default: No Default

**time\_step\_proportions** the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

Type: constant vector

Default: true

**type** Type

Type: string

Default: No Default

### 8.8.1. @age\_length[label].type=data

**by\_length** Specifies if the linear interpolation of CV's is a linear function of mean length at age. Default is just by age

Type: boolean

Default: true

**casal\_switch** A switch to use CASAL Cumulative normal function, note CASAL2 uses the

recent BOOST function which differs from the previous CASAL algorithm

Type: boolean

Default: false

cv\_first      CV for the first age class

Type: constant

Default: Double(0.0

Lower Bound: 0.0 (inclusive)

cv\_last      CV for last age class

Type: constant

Default: Double(0.0

Lower Bound: 0.0 (inclusive)

distribution      The assumed distribution for the growth curve

Type: string

Default: normal

external\_gaps

Type: string

Default: mean

Allowed Values: mean, nearest\_neighbour

internal\_gaps

Type: string

Default: mean

Allowed Values: mean, nearest\_neighbour, interpolate

length\_weight      The label from an associated length-weight block

Type: string

Default: No Default

time\_step\_proportions      the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

Type: constant vector

Default: true

### 8.8.2. @age\_\_length[label].type=None

casal\_switch      A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm

Type: boolean

Default: false

cv\_first      CV for the first age class

Type: constant  
Default: Double(0.0)  
Lower Bound: 0.0 (inclusive)

`cv_last`      CV for last age class  
Type: constant  
Default: Double(0.0)  
Lower Bound: 0.0 (inclusive)

`distribution`      The assumed distribution for the growth curve  
Type: string  
Default: normal

`time_step_proportions`      the proportion increase of age through the in each time step that corresponds to a length and thus weight increase  
Type: constant vector  
Default: true

### **8.8.3. @age\_\_length[label].type=schnute**

a      Define the  $a$  parameter of the Schnute relationship  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (inclusive)

b      Define the  $b$  parameter of the Schnute relationship  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (exclusive)

`by_length`      Specifies if the linear interpolation of CV's is a linear function of mean length at age. Default is just by age  
Type: boolean  
Default: true

`casal_switch`      A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm  
Type: boolean  
Default: false

`cv_first`      CV for the first age class  
Type: constant  
Default: Double(0.0)  
Lower Bound: 0.0 (inclusive)



`cv_last` CV for last age class

Type: constant

Default: Double(0.0

Lower Bound: 0.0 (inclusive)

`distribution` The assumed distribution for the growth curve

Type: string

Default: normal

`length_weight` Define the label of the associated length-weight relationship

Type: string

Default: No Default

`tau1` Define the  $\tau_1$  parameter of the Schnute relationship

Type: constant

Default: No Default

`tau2` Define the  $\tau_2$  parameter of the Schnute relationship

Type: constant

Default: No Default

`time_step_proportions` the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

Type: constant vector

Default: true

`y1` Define the  $y_1$  parameter of the Schnute relationship

Type: constant

Default: No Default

`y2` Define the  $y_2$  parameter of the Schnute relationship

Type: constant

Default: No Default

#### **8.8.4. @age\_length[label].type=von bertalanffy**

`by_length` Specifies if the linear interpolation of CV's is a linear function of mean length at age. Default is just by age

Type: boolean

Default: true

`casal_switch` A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm

Type: boolean

Default: false

`cv_first`      CV for the first age class

Type: constant

Default: Double(0.0)

Lower Bound: 0.0 (inclusive)

`cv_last`      CV for last age class

Type: constant

Default: Double(0.0)

Lower Bound: 0.0 (inclusive)

`distribution`      The assumed distribution for the growth curve

Type: string

Default: normal

`k`      Define the  $k$  parameter of the von Bertalanffy relationship

Type: constant

Default: No Default

Lower Bound: 0.0 (inclusive)

`length_weight`      Define the label of the associated length-weight relationship

Type: string

Default: No Default

`linf`      Define the  $L_{infinity}$  parameter of the von Bertalanffy relationship

Type: constant

Default: No Default

Lower Bound: 0.0 (inclusive)

`t0`      Define the  $t_0$  parameter of the von Bertalanffy relationship

Type: constant

Default: No Default

`time_step_proportions`      the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

Type: constant vector

Default: true

## 8.9. Length-weight

**@length\_weight** *label*      Define an object type Length\_Weight

*label*      Label

Type: string

Default: No Default

type      Type  
Type: string  
Default: No Default

### 8.9.1. @length\_weight[label].type=basic

a      A  
Type: constant  
Default: No Default

b      B  
Type: constant  
Default: No Default

units      Units of measure (tonnes, kgs, grams  
Type: string  
Default: No Default

### 8.9.2. @length\_weight[label].type=none

## 8.10. Selectivities

**@selectivity** *label*      Define an object type Selectivity

label      Label  
Type: string  
Default: No Default

length\_based      Is the selectivity length based  
Type: boolean  
Default: false

intervals      Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
Type: non-negative integer  
Default: 5

type      Type  
Type: string  
Default: No Default

### 8.10.1. `@selectivity[label].type=all_values`

`length_based`      Is the selectivity length based

Type: boolean

Default: false

`intervals`      Number of quantiles to evaluate a length based selectivity over the age length distribution

Type: non-negative integer

Default: 5

`v`      `V`

Type: constant vector

Default: No Default

### 8.10.2. `@selectivity[label].type=all_values_bounded`

`h`      `H`

Type: non-negative integer

Default: No Default

`length_based`      Is the selectivity length based

Type: boolean

Default: false

`l`      `L`

Type: non-negative integer

Default: No Default

`intervals`      Number of quantiles to evaluate a length based selectivity over the age length distribution

Type: non-negative integer

Default: 5

`v`      `V`

Type: constant vector

Default: No Default

### 8.10.3. `@selectivity[label].type=constant`

`c`      `C`

Type: constant

Default: No Default

length\_based      Is the selectivity length based  
Type: boolean  
Default: false

intervals          Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
Type: non-negative integer  
Default: 5

#### **8.10.4. @selectivity[label].type=double.exponential**

alpha      Alpha  
Type: constant  
Default: 1.0

length\_based      Is the selectivity length based  
Type: boolean  
Default: false

intervals          Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
Type: non-negative integer  
Default: 5

x0      X0  
Type: constant  
Default: No Default

x1      X1  
Type: constant  
Default: No Default

x2      X2  
Type: constant  
Default: No Default

y0      Y0  
Type: constant  
Default: No Default

y1      Y1  
Type: constant  
Default: No Default

y2      Y2

Type: constant  
Default: No Default

#### **8.10.5. @selectivity[label].type=double normal**

alpha     Alpha  
Type: constant  
Default: 1.0

length\_based     Is the selectivity length based  
Type: boolean  
Default: false

mu     Mu  
Type: constant  
Default: No Default

intervals     Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
Type: non-negative integer  
Default: 5

sigma\_l     Sigma L  
Type: constant  
Default: No Default

sigma\_r     Sigma R  
Type: constant  
Default: No Default

#### **8.10.6. @selectivity[label].type=increasing**

alpha     Alpha  
Type: constant  
Default: 1.0

h     High  
Type: non-negative integer  
Default: No Default

length\_based     Is the selectivity length based  
Type: boolean  
Default: false

l      Low  
Type: non-negative integer  
Default: No Default

intervals      Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
Type: non-negative integer  
Default: 5

v      V  
Type: constant vector  
Default: No Default

#### **8.10.7. @selectivity[label].type=inverse\_logistic**

a50      A50  
Type: constant  
Default: No Default

alpha      Alpha  
Type: constant  
Default: 1.0

ato95      aTo95  
Type: constant  
Default: No Default

length\_based      Is the selectivity length based  
Type: boolean  
Default: false

intervals      Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
Type: non-negative integer  
Default: 5

#### **8.10.8. @selectivity[label].type=knife\_edge**

alpha      Alpha  
Type: constant  
Default: 1.0

e      Edge

Type: constant

Default: No Default

length\_based      Is the selectivity length based

Type: boolean

Default: false

intervals      Number of quantiles to evaluate a length based selectivity over the age length distribution

Type: non-negative integer

Default: 5

#### **8.10.9. @selectivity[label].type=logistic**

a50      A50

Type: constant

Default: No Default

alpha      Alpha

Type: constant

Default: 1.0

ato95      Ato95

Type: constant

Default: No Default

length\_based      Is the selectivity length based

Type: boolean

Default: false

intervals      Number of quantiles to evaluate a length based selectivity over the age length distribution

Type: non-negative integer

Default: 5

#### **8.10.10. @selectivity[label].type=logistic\_producing**

a50      A50

Type: constant

Default: No Default

alpha      Alpha

Type: constant

Default: 1.0



---

ato95      Ato95  
Type: constant  
Default: No Default

h      High  
Type: non-negative integer  
Default: No Default

length\_based      Is the selectivity length based  
Type: boolean  
Default: false

l      Low  
Type: non-negative integer  
Default: No Default

intervals      Number of quantiles to evaluate a length based selectivity over the age length distribution  
Type: non-negative integer  
Default: 5

## 9. Estimation command and subcommand syntax

### 9.1. Estimation methods

**@estimate** *label*      Define an object type Estimate

estimation\_phase      TBA  
Type: non-negative integer  
Default: 1u

label      Label  
Type: string  
Default: ""

lower\_bound      The lowest value the parameter is allowed to have  
Type: constant  
Default: No Default

mcmc      This parameter fixes parameters during an MCMC run  
Type: boolean  
Default: false

parameter      The name of the variable to estimate in the model

Type: string  
Default: No Default

`prior`      The name of the prior to use for the parameter  
Type: string  
Default: ""

`same`      A list of parameters that are bound to the value of this estimate  
Type: string vector  
Default: ""

`type`      Type  
Type: string  
Default: No Default

`upper_bound`      The highest value the parameter is allowed to have  
Type: constant  
Default: No Default

### 9.1.1. `@estimate[label].type=beta`

`a`      A  
Type: constant  
Default: No Default

`b`      B  
Type: constant  
Default: No Default

`estimation_phase`      TBA  
Type: non-negative integer  
Default: 1u

`lower_bound`      The lowest value the parameter is allowed to have  
Type: constant  
Default: No Default

`mcmc`      This parameter fixes parameters during an MCMC run  
Type: boolean  
Default: false

`mu`      Mu  
Type: constant  
Default: No Default

`parameter`    The name of the variable to estimate in the model  
Type: string  
Default: No Default

`prior`        The name of the prior to use for the parameter  
Type: string  
Default: ""

`same`        A list of parameters that are bound to the value of this estimate  
Type: string vector  
Default: ""

`sigma`        Sigma  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (exclusive)

`upper_bound`    The highest value the parameter is allowed to have  
Type: constant  
Default: No Default

### 9.1.2. @estimate[label].type=lognormal

`cv`            Cv  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (exclusive)

`estimation_phase`    TBA  
Type: non-negative integer  
Default: 1u

`lower_bound`    The lowest value the parameter is allowed to have  
Type: constant  
Default: No Default

`mcmc`        This parameter fixes parameters during an MCMC run  
Type: boolean  
Default: false

`mu`            Mu  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (exclusive)

`parameter`    The name of the variable to estimate in the model  
                  Type: string  
                  Default: No Default

`prior`        The name of the prior to use for the parameter  
                  Type: string  
                  Default: ""

`same`         A list of parameters that are bound to the value of this estimate  
                  Type: string vector  
                  Default: ""

`upper_bound`    The highest value the parameter is allowed to have  
                  Type: constant  
                  Default: No Default

### 9.1.3. **@estimate[label].type=normal**

`cv`            Cv  
                  Type: constant  
                  Default: No Default  
                  Lower Bound: 0.0 (exclusive)

`estimation_phase`    TBA  
                  Type: non-negative integer  
                  Default: 1u

`lower_bound`    The lowest value the parameter is allowed to have  
                  Type: constant  
                  Default: No Default

`mcmc`         This parameter fixes parameters during an MCMC run  
                  Type: boolean  
                  Default: false

`mu`            Mu  
                  Type: constant  
                  Default: No Default

`parameter`    The name of the variable to estimate in the model  
                  Type: string  
                  Default: No Default

`prior`        The name of the prior to use for the parameter

Type: string  
Default: ""

same      A list of parameters that are bound to the value of this estimate  
Type: string vector  
Default: ""

upper\_bound      The highest value the parameter is allowed to have  
Type: constant  
Default: No Default

#### 9.1.4. `@estimate[label].type=normal_by_stdev`

estimation\_phase      TBA  
Type: non-negative integer  
Default: 1u

lower\_bound      The lowest value the parameter is allowed to have  
Type: constant  
Default: No Default

mcmc      This parameter fixes parameters during an MCMC run  
Type: boolean  
Default: false

mu      Mu  
Type: constant  
Default: No Default

parameter      The name of the variable to estimate in the model  
Type: string  
Default: No Default

prior      The name of the prior to use for the parameter  
Type: string  
Default: ""

same      A list of parameters that are bound to the value of this estimate  
Type: string vector  
Default: ""

sigma      Sigma  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (exclusive)

`upper_bound`     The highest value the parameter is allowed to have  
Type: constant  
Default: No Default

#### 9.1.5. `@estimate[label].type=normal_log`

`estimation_phase`     TBA  
Type: non-negative integer  
Default: 1u

`lower_bound`     The lowest value the parameter is allowed to have  
Type: constant  
Default: No Default

`mcmc`     This parameter fixes parameters during an MCMC run  
Type: boolean  
Default: false

`mu`     Mu  
Type: constant  
Default: No Default

`parameter`     The name of the variable to estimate in the model  
Type: string  
Default: No Default

`prior`     The name of the prior to use for the parameter  
Type: string  
Default: ""

`same`     A list of parameters that are bound to the value of this estimate  
Type: string vector  
Default: ""

`sigma`     Sigma  
Type: constant  
Default: No Default  
Lower Bound: 0.0 (exclusive)

`upper_bound`     The highest value the parameter is allowed to have  
Type: constant  
Default: No Default

**9.1.6. @estimate[label].type=uniform**

estimation\_phase    TBA

Type: non-negative integer

Default: 1u

lower\_bound    The lowest value the parameter is allowed to have

Type: constant

Default: No Default

mcmc    This parameter fixes parameters during an MCMC run

Type: boolean

Default: false

parameter    The name of the variable to estimate in the model

Type: string

Default: No Default

prior    The name of the prior to use for the parameter

Type: string

Default: ""

same    A list of parameters that are bound to the value of this estimate

Type: string vector

Default: ""

upper\_bound    The highest value the parameter is allowed to have

Type: constant

Default: No Default

**9.1.7. @estimate[label].type=uniform\_log**

estimation\_phase    TBA

Type: non-negative integer

Default: 1u

lower\_bound    The lowest value the parameter is allowed to have

Type: constant

Default: No Default

mcmc    This parameter fixes parameters during an MCMC run

Type: boolean

Default: false

parameter    The name of the variable to estimate in the model

Type: string  
Default: No Default

`prior`      The name of the prior to use for the parameter  
Type: string  
Default: ""

`same`      A list of parameters that are bound to the value of this estimate  
Type: string vector  
Default: ""

`upper_bound`      The highest value the parameter is allowed to have  
Type: constant  
Default: No Default

## 9.2. Point estimation

**@`minimiser` *label***      Define an object type `Minimiser`

`active`      True if this minimiser is active  
Type: boolean  
Default: false

`covariance`      True if a covariance matrix should be created  
Type: boolean  
Default: true

`label`      Label  
Type: string  
Default: No Default

`type`      Type of minimiser to use  
Type: string  
Default: No Default

### 9.2.1. **@`minimiser`[*label*].`type=adolc`**

`active`      True if this minimiser is active  
Type: boolean  
Default: false

`covariance`      True if a covariance matrix should be created  
Type: boolean  
Default: true



tolerance     Tolerance of the gradient for convergence  
Type: constant  
Default: 0.02

evaluations     Maximum number of evaluations  
Type: integer  
Default: 4000

iterations     Maximum number of iterations  
Type: integer  
Default: 1000

step\_size     Minimum Step-size before minimisation fails  
Type: constant  
Default: 1e-7

### 9.2.2. @minimiser[label].type=betadiff

active     True if this minimiser is active  
Type: boolean  
Default: false

covariance     True if a covariance matrix should be created  
Type: boolean  
Default: true

tolerance     Tolerance of the gradient for convergence  
Type: constant  
Default: 2e-3

evaluations     Maximum number of evaluations  
Type: integer  
Default: 4000

iterations     Maximum number of iterations  
Type: integer  
Default: 1000

### 9.2.3. @minimiser[label].type=cppad

active     True if this minimiser is active  
Type: boolean  
Default: false

`covariance`      True if a covariance matrix should be created  
Type: boolean  
Default: true

#### 9.2.4. `@minimiser[label].type=de_solver`

`active`      True if this minimiser is active  
Type: boolean  
Default: false

`covariance`      True if a covariance matrix should be created  
Type: boolean  
Default: true

`crossover_probability`      Define the minimisers crossover probability  
Type: constant  
Default: 0.9

`difference_scale`      The scale to apply to new solutions when comparing candidates  
Type: constant  
Default: 0.02

`max_generations`      The maximum number of iterations to run  
Type: non-negative integer  
Default: No Default

`method`      The type of candidate generation method to use  
Type: string  
Default: ""  
Value: not\_yet\_implemented

`population_size`      The number of candidate solutions to have in the population  
Type: non-negative integer  
Default: No Default

`tolerance`      The total variance between the population and best candidate before acceptance  
Type: constant  
Default: 0.01

#### 9.2.5. `@minimiser[label].type=dlib`

`active`      True if this minimiser is active  
Type: boolean  
Default: false

covariance    True if a covariance matrix should be created  
Type: boolean  
Default: true

#### 9.2.6. @minimiser[label].type=numerical\_differences

active        True if this minimiser is active  
Type: boolean  
Default: false

covariance    True if a covariance matrix should be created  
Type: boolean  
Default: true

tolerance     Tolerance of the gradient for convergence  
Type: constant  
Default: 0.02

evaluations   Maximum number of evaluations  
Type: integer  
Default: 4000

iterations     Maximum number of iterations  
Type: integer  
Default: 1000

step\_size     Minimum Step-size before minimisation fails  
Type: constant  
Default: 1e-7

### 9.3. Monte Carlo Markov Chain (MCMC)

@mcmc label    Define an object type MCMC

active        Is this the active MCMC algorithm  
Type: boolean  
Default: true

label        Label  
Type: string  
Default: No Default

length        The number of chain links to create

Type: non-negative integer  
Default: No Default

`print_default_reports`  
Type: boolean  
Default: true

`type`     Type  
Type: string  
Default: ""

### 9.3.1. `@mcmc[label].type=independence metropolis`

`active`     Is this the active MCMC algorithm  
Type: boolean  
Default: true

`adapt_covariance_matrix_at`     Iterations in the chain to check and resize the MCMC stepsize  
Type: non-negative integer vector  
Default: true

`adapt_stepsize_at`     Iterations in the chain to check and resize the MCMC stepsize  
Type: non-negative integer vector  
Default: true

`correlation_adjustment_diff`     Minimum non-zero variance times the range of the bounds in the covariance matrix of the proposal distribution  
Type: constant  
Default: 0.0001

`covariance_adjustment_method`     Method for adjusting small variances in the covariance proposal matrix  
Type: string  
Default: covariance

`df`     Degrees of freedom of the multivariate t proposal distribution  
Type: non-negative integer  
Default: 4

`keep`     Spacing between recorded values in the chain  
Type: non-negative integer  
Default: 1u

`length`     The number of chain links to create

Type: non-negative integer  
Default: No Default

`max_correlation`      Maximum absolute correlation in the covariance matrix of the proposal distribution  
Type: constant  
Default: 0.8

`print_default_reports`  
Type: boolean  
Default: true

`proposal_distribution`      The shape of the proposal distribution (either t or normal)  
Type: string  
Default: t

`start`      Covariance multiplier for the starting point of the Markov chain  
Type: constant  
Default: 0.0

`step_size`      Initial stepsize (as a multiplier of the approximate covariance matrix)  
Type: constant  
Default: 0.02

## 9.4. Profiles

**@profile** *label*      Define an object type Profile

`label`      Label  
Type: string  
Default: ""

`lower_bound`      The lower bounds  
Type: constant  
Default: No Default

`parameter`      The system parameter to profile  
Type: string  
Default: No Default

`steps`      The number of steps to take between the lower and upper bound  
Type: non-negative integer  
Default: No Default

`type`

Type: string  
Default: No Default

`upper_bound`      The upper bounds  
Type: constant  
Default: No Default

## 9.5. Defining catchability constants

**@catchability** *label*      Define an object type Catchability

`label`      Label  
Type: string  
Default: No Default

`type`  
Type: string  
Default: No Default

### 9.5.1. @catchability[label].type=free

`q`      The catchability amount  
Type: constant  
Default: No Default

## 9.6. Defining penalties

**@penalty** *label*      Define an object type Penalty

`label`      Label  
Type: string  
Default: No Default

`type`      Type  
Type: string  
Default: No Default

### 9.6.1. @penalty[label].type=process

`log_scale`      Log scale  
Type: boolean  
Default: false

multiplier      Multiplier  
 Type: constant  
 Default: 1.0

## 9.7. Defining priors on parameter ratios, differences and means

**@additional\_prior** *label*      Define an object type Additional\_Prior

label      Label  
 Type: string  
 Default: No Default

type      Type  
 Type: string  
 Default: No Default

### 9.7.1. @additional\_prior[label].type=beta

a      A  
 Type: constant  
 Default: No Default

b      B  
 Type: constant  
 Default: No Default

mu      Mu  
 Type: constant  
 Default: No Default

sigma      Sigma  
 Type: constant  
 Default: No Default  
 Lower Bound: 0.0 (inclusive)

### 9.7.2. @additional\_prior[label].type=vector\_average

k      K Value to use in the calculation  
 Type: constant  
 Default: No Default

method      What calculation method to use (k, l, m)  
 Type: string  
 Default: k

`multiplier`      Multiplier for the penalty amount  
Type: constant  
Default: 1

`parameter`      Label of the estimate to generate penalty on  
Type: string  
Default: No Default

### 9.7.3. `@additional_prior[label].type=vector_smoothing`

`log_scale`      Log scale  
Type: boolean  
Default: false

`lower_bound`      First element to apply the penalty to in the vector  
Type: non-negative integer  
Default: 0u

`multiplier`      Multiplier for the penalty amount  
Type: constant  
Default: 1

`parameter`      Label of the estimate to generate penalty on  
Type: string  
Default: No Default

`r`      Penalty applied to rth differences  
Type: non-negative integer  
Default: 2u

`upper_bound`      Last element to apply the penalty to in the vector  
Type: non-negative integer  
Default: 0u

## 10. Observation command and subcommand syntax

### 10.1. Observation types

The observation types available are,

Observations of proportions of individuals by age class

Observations of proportions of individuals between categories within each age class



Relative and absolute abundance observations

Relative and absolute biomass observations

Each type of observation requires a set of subcommands and arguments specific to that process.

**@observation** *label*     Define an object type Observation

*categories*     Category labels to use

Type: string vector

Default: true

*error\_value\_multiplier*     Error value multiplier for likelihood

Type: constant

Default: Double(1.0)

*label*     Label

Type: string

Default: No Default

*likelihood\_multiplier*     Likelihood score multiplier

Type: constant

Default: Double(1.0)

*likelihood*     Type of likelihood to use

Type: string

Default: No Default

*simulation\_likelihood*     Simulation likelihood to use

Type: string

Default: ""

*type*     Type of observation

Type: string

Default: No Default

### 10.1.1. @observation[label].type=process\_abundance

*catchability*     Abundance catchability

Type: string

Default: No Default

*categories*     Category labels to use

Type: string vector

Default: true

*delta*     Delta value for error values

Type: constant

Default: Double(1e-10)

`error_value_multiplier`      Error value multiplier for likelihood

Type: constant

Default: Double(1.0)

`error_value`      The error values to use against the observation values

Type: constant vector

Default: No Default

`likelihood_multiplier`      Likelihood score multiplier

Type: constant

Default: Double(1.0)

`likelihood`      Type of likelihood to use

Type: string

Default: No Default

`obs`      Observation values

Type: string vector

Default: No Default

`process_error`      Process error

Type: constant

Default: Double(0.0)

`process`      Process label

Type: string

Default: No Default

`process_proportion`      Process proportion

Type: constant

Default: Double(0.5)

`selectivities`      Selectivity labels to use

Type: string vector

Default: true

`simulation_likelihood`      Simulation likelihood to use

Type: string

Default: ""

`time_step`      Time step to execute in

Type: string  
Default: No Default

years      Years to execute in  
Type: non-negative integer vector  
Default: No Default

### 10.1.2. `@observation[label].type=time_step_abundance`

catchability      Catchability label for this observation  
Type: string  
Default: No Default

categories      Category labels to use  
Type: string vector  
Default: true

delta      Delta value for error values  
Type: constant  
Default: Double(1e-10)

error\_value\_multiplier      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

error\_value      The error values to use against the observation values  
Type: constant vector  
Default: No Default

likelihood\_multiplier      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

likelihood      Type of likelihood to use  
Type: string  
Default: No Default

obs      Observation values  
Type: string vector  
Default: No Default

process\_error      Process error  
Type: constant  
Default: Double(0.0)

`selectivities`      Selectivity labels to use  
Type: string vector  
Default: true

`simulation_likelihood`      Simulation likelihood to use  
Type: string  
Default: ""

`time_step`      Time step to execute in  
Type: string  
Default: No Default

`time_step_proportion`      Proportion through the time step to analyse the partition from  
Type: constant  
Default: Double(0.5)

`years`      Years to execute in  
Type: non-negative integer vector  
Default: No Default

### 10.1.3. `@observation[label].type=process_biomass`

`catchability`      Catchability of Biomass  
Type: string  
Default: No Default

`categories`      Category labels to use  
Type: string vector  
Default: true

`delta`      Delta value for error values  
Type: constant  
Default: Double(1e-10)

`error_value_multiplier`      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

`error_value`      The error values to use against the observation values  
Type: constant vector  
Default: No Default

`likelihood_multiplier`      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

`likelihood`      Type of likelihood to use  
Type: string  
Default: No Default

`obs`      Observation values  
Type: string vector  
Default: No Default

`process_error`      Process error  
Type: constant  
Default: Double(0.0)

`process`      Process label  
Type: string  
Default: No Default

`process_proportion`      Process proportion  
Type: constant  
Default: Double(0.5)

`selectivities`      Selectivity labels to use  
Type: string vector  
Default: true

`simulation_likelihood`      Simulation likelihood to use  
Type: string  
Default: ""

`time_step`      Time step to execute in  
Type: string  
Default: No Default

`years`      Years to execute in  
Type: non-negative integer vector  
Default: No Default

#### 10.1.4. `@observation[label].type=time_step_biomass`

`catchability`      Catchability of Biomass  
Type: string  
Default: No Default

`categories`      Category labels to use

Type: string vector  
Default: true

delta      Delta value for error values  
Type: constant  
Default: Double(1e-10)

error\_value\_multiplier      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

error\_value      The error values to use against the observation values  
Type: constant vector  
Default: No Default

likelihood\_multiplier      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

likelihood      Type of likelihood to use  
Type: string  
Default: No Default

obs      Observation values  
Type: string vector  
Default: No Default

process\_error      Process error  
Type: constant  
Default: Double(0.0)

selectivities      Selectivity labels to use  
Type: string vector  
Default: true

simulation\_likelihood      Simulation likelihood to use  
Type: string  
Default: ""

time\_step      Time step to execute in  
Type: string  
Default: No Default

time\_step\_proportion      Proportion through the time step to analyse the partition from

Type: constant  
Default: Double(0.5)

years      Years to execute in  
Type: non-negative integer vector  
Default: No Default

### 10.1.5. @observation[label].type=process\_proportions\_at\_age

age\_plus      Use age plus group  
Type: boolean  
Default: true

ageing\_error      Label of ageing error to use  
Type: string  
Default: ""

categories      Category labels to use  
Type: string vector  
Default: true

delta      Delta  
Type: constant  
Default: DELTA

error\_value\_multiplier      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

likelihood\_multiplier      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

likelihood      Type of likelihood to use  
Type: string  
Default: No Default

max\_age      Maximum age  
Type: non-negative integer  
Default: No Default

min\_age      Minimum age  
Type: non-negative integer  
Default: No Default

`process_errors`      Process error  
Type: constant vector  
Default: true

`process`      Process label  
Type: string  
Default: No Default

`process_proportion`      Process proportion  
Type: constant  
Default: Double(0.5)

`selectivities`      Selectivity labels to use  
Type: string vector  
Default: true

`simulation_likelihood`      Simulation likelihood to use  
Type: string  
Default: ""

`time_step`      Time step to execute in  
Type: string  
Default: No Default

`tolerance`      Tolerance  
Type: constant  
Default: Double(0.001)

`years`      Year to execute in  
Type: non-negative integer vector  
Default: No Default

#### **10.1.6. `@observation[label].type=time_step_proportions_at_age`**

`age_plus`      Use age plus group  
Type: boolean  
Default: true

`ageing_error`      Label of ageing error to use  
Type: string  
Default: ""

`categories`      Category labels to use  
Type: string vector  
Default: true



delta	Delta
Type: constant	
Default: DELTA	
error_value_multiplier	Error value multiplier for likelihood
Type: constant	
Default: Double(1.0	
likelihood_multiplier	Likelihood score multiplier
Type: constant	
Default: Double(1.0	
likelihood	Type of likelihood to use
Type: string	
Default: No Default	
max_age	Maximum age
Type: non-negative integer	
Default: No Default	
min_age	Minimum age
Type: non-negative integer	
Default: No Default	
process_errors	Process error
Type: constant vector	
Default: true	
selectivities	Selectivity labels to use
Type: string vector	
Default: true	
simulation_likelihood	Simulation likelihood to use
Type: string	
Default: ""	
time_step	Time step to execute in
Type: string	
Default: No Default	
time_step_proportion	Proportion through the time step to analyse the partition from
Type: constant	
Default: Double(0.5	

tolerance      Tolerance

Type: constant

Default: Double(0.001)

years      Year to execute in

Type: non-negative integer vector

Default: No Default

### **10.1.7. @observation[label].type=proportions\_at\_age\_for\_fishery**

age\_plus      Use age plus group

Type: boolean

Default: true

ageing\_error      Label of ageing error to use

Type: string

Default: ""

categories      Category labels to use

Type: string vector

Default: true

delta      Delta

Type: constant

Default: DELTA

error\_value\_multiplier      Error value multiplier for likelihood

Type: constant

Default: Double(1.0)

fishery      Label of fishery the observation is from

Type: string vector

Default: ""

likelihood\_multiplier      Likelihood score multiplier

Type: constant

Default: Double(1.0)

likelihood      Type of likelihood to use

Type: string

Default: No Default

max\_age      Maximum age

Type: non-negative integer

Default: No Default

min\_age      Minimum age

Type: non-negative integer

Default: No Default

process\_errors      Process error

Type: constant vector

Default: true

process      Process label

Type: string

Default: No Default

simulation\_likelihood      Simulation likelihood to use

Type: string

Default: ""

time\_step      Time steps that the fisheries are in

Type: string vector

Default: No Default

tolerance      Tolerance

Type: constant

Default: Double(0.001)

years      Year to execute in

Type: non-negative integer vector

Default: No Default

### **10.1.8. @observation[label].type=process\_proportions\_at\_length**

categories      Category labels to use

Type: string vector

Default: true

delta      Delta

Type: constant

Default: DELTA

error\_value\_multiplier      Error value multiplier for likelihood

Type: constant

Default: Double(1.0)

length\_bins      Length bins

Type: constant vector  
Default: No Default

length\_plus\_group      Is the last bin a plus group  
Type: boolean  
Default: true

likelihood\_multiplier      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

likelihood      Type of likelihood to use  
Type: string  
Default: No Default

process\_errors      Process error  
Type: constant vector  
Default: true

process      Process label  
Type: string  
Default: No Default

process\_proportion      Process proportion  
Type: constant  
Default: Double(0.5)

selectivities      Selectivity labels to use  
Type: string vector  
Default: true

simulation\_likelihood      Simulation likelihood to use  
Type: string  
Default: ""

time\_step      Time step to execute in  
Type: string  
Default: No Default

tolerance      Tolerance for rescaling proportions  
Type: constant  
Default: Double(0.001)

years      Year to execute in

Type: non-negative integer vector

Default: No Default

### 10.1.9. `@observation[label].type=time_step_proportions_at_length`

`categories`      Category labels to use

Type: string vector

Default: true

`delta`      Delta

Type: constant

Default: DELTA

`error_value_multiplier`      Error value multiplier for likelihood

Type: constant

Default: Double(1.0)

`length_bins`      Length bins

Type: constant vector

Default: No Default

`length_plus_group`      Is the last bin a plus group

Type: boolean

Default: true

`likelihood_multiplier`      Likelihood score multiplier

Type: constant

Default: Double(1.0)

`likelihood`      Type of likelihood to use

Type: string

Default: No Default

`process_errors`      Process error

Type: constant vector

Default: true

`selectivities`      Selectivity labels to use

Type: string vector

Default: true

`simulation_likelihood`      Simulation likelihood to use

Type: string

Default: ""

`time_step`      Time step to execute in  
Type: string  
Default: No Default

`time_step_proportion`      Proportion through the time step to analyse the partition from  
Type: constant  
Default: Double(0.5)

`tolerance`      Tolerance for rescaling proportions  
Type: constant  
Default: Double(0.001)

`years`      Year to execute in  
Type: non-negative integer vector  
Default: No Default

#### **10.1.10. `@observation[label].type=proportions_at_length_for_fishery`**

`categories`      Category labels to use  
Type: string vector  
Default: true

`delta`      Delta  
Type: constant  
Default: DELTA

`error_value_multiplier`      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

`fishery`      Label of fishery the observation is from  
Type: string  
Default: ""

`length_bins`      Length bins  
Type: constant vector  
Default: No Default

`length_plus_group`      Is the last bin a plus group  
Type: boolean  
Default: true

`likelihood_multiplier`      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

`likelihood`      Type of likelihood to use  
Type: string  
Default: No Default

`process_errors`      Process error  
Type: constant vector  
Default: true

`process`      Process label  
Type: string  
Default: No Default

`process_proportion`      Process proportion  
Type: constant  
Default: Double(0.5)

`simulation_likelihood`      Simulation likelihood to use  
Type: string  
Default: ""

`time_step`      Time step to execute in  
Type: string  
Default: No Default

`tolerance`      Tolerance for rescaling proportions  
Type: constant  
Default: Double(0.001)

`years`      Year to execute in  
Type: non-negative integer vector  
Default: No Default

#### 10.1.11. `@observation[label].type=process_proportions_by_category`

`age_plus`      Use age plus group  
Type: boolean  
Default: true

`categories`      Category labels to use  
Type: string vector  
Default: true

`delta`      Delta

Type: constant  
Default: DELTA  
Lower Bound: 0.0 (exclusive)

`error_value_multiplier`      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

`likelihood_multiplier`      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

`likelihood`      Type of likelihood to use  
Type: string  
Default: No Default

`max_age`      Maximum age  
Type: non-negative integer  
Default: No Default

`min_age`      Minimum age  
Type: non-negative integer  
Default: No Default

`process_errors`      Process error  
Type: constant vector  
Default: true

`process`      Process label  
Type: string  
Default: No Default

`process_proportion`      Process proportion  
Type: constant  
Default: Double(0.5)

`selectivities`      Selectivity labels to use  
Type: string vector  
Default: true

`simulation_likelihood`      Simulation likelihood to use  
Type: string  
Default: ""

`categories2`      Target Categories



Type: string vector  
Default: No Default

`selectivities2`      Target Selectivities

Type: string vector  
Default: No Default

`time_step`      Time step to execute in

Type: string  
Default: No Default

`years`      Year to execute in

Type: non-negative integer vector  
Default: No Default

#### 10.1.12. `@observation[label].type=time_step_proportions_by_category`

`age_plus`      Use age plus group

Type: boolean  
Default: true

`categories`      Category labels to use

Type: string vector  
Default: true

`delta`      Delta

Type: constant  
Default: DELTA  
Lower Bound: 0.0 (exclusive)

`error_value_multiplier`      Error value multiplier for likelihood

Type: constant  
Default: Double(1.0)

`likelihood_multiplier`      Likelihood score multiplier

Type: constant  
Default: Double(1.0)

`likelihood`      Type of likelihood to use

Type: string  
Default: No Default

`max_age`      Maximum age

Type: non-negative integer  
Default: No Default

`min_age`      Minimum age

Type: non-negative integer

Default: No Default

`process_errors`      Process error

Type: constant vector

Default: true

`selectivities`      Selectivity labels to use

Type: string vector

Default: true

`simulation_likelihood`      Simulation likelihood to use

Type: string

Default: ""

`categories2`      Target Categories

Type: string vector

Default: No Default

`selectivities2`      Target Selectivities

Type: string vector

Default: No Default

`time_step`      Time step to execute in

Type: string

Default: No Default

`time_step_proportion`      Proportion through the time step to analyse the partition from

Type: constant

Default: Double(0.5)

`years`      Year to execute in

Type: non-negative integer vector

Default: No Default

### **10.1.13. @observation[label].type=proportions\_migrating**

`age_plus`      Use age plus group

Type: boolean

Default: true

`ageing_error`      Label of ageing error to use

Type: string  
Default: ""

categories      Category labels to use  
Type: string vector  
Default: true

delta      Delta  
Type: constant  
Default: DELTA

error\_value\_multiplier      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

likelihood\_multiplier      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

likelihood      Type of likelihood to use  
Type: string  
Default: No Default

max\_age      Maximum age  
Type: non-negative integer  
Default: No Default

min\_age      Minimum age  
Type: non-negative integer  
Default: No Default

process\_errors      Process error  
Type: constant vector  
Default: true

process      Process label  
Type: string  
Default: No Default

process\_proportion      Process proportion  
Type: constant  
Default: Double(0.5)

simulation\_likelihood      Simulation likelihood to use

Type: string  
 Default: ""

`time_step`      Time step to execute in  
 Type: string  
 Default: No Default

`years`          Year to execute in  
 Type: non-negative integer vector  
 Default: No Default

#### 10.1.14. `@observation[label].type=tag_recapture_by_age`

`age_plus`        Use age plus group  
 Type: boolean  
 Default: true

`categories`     Category labels to use  
 Type: string vector  
 Default: true

`delta`          Delta  
 Type: constant  
 Default: DELTA  
 Lower Bound: 0.0 (exclusive)

`detection`      Detection probability  
 Type: constant  
 Default: No Default

`error_value_multiplier`      Error value multiplier for likelihood  
 Type: constant  
 Default: Double(1.0)

`likelihood_multiplier`      Likelihood score multiplier  
 Type: constant  
 Default: Double(1.0)

`likelihood`     Type of likelihood to use  
 Type: string  
 Default: No Default

`max_age`        Maximum age  
 Type: non-negative integer  
 Default: No Default

`min_age` Minimum age

Type: non-negative integer

Default: No Default

`process_errors` Process error

Type: constant vector

Default: true

`selectivities` Selectivity labels to use

Type: string vector

Default: true

`simulation_likelihood` Simulation likelihood to use

Type: string

Default: ""

`categories2` Target Categories

Type: string vector

Default: No Default

`selectivities2` Target Selectivities

Type: string vector

Default: No Default

`time_step` Time step to execute in

Type: string

Default: No Default

`time_step_proportion` Proportion through the time step to analyse the partition from

Type: constant

Default: Double(0.5)

`years` Year to execute in

Type: non-negative integer vector

Default: No Default

#### 10.1.15. `@observation[label].type=tag_recapture_by_length`

`categories` Category labels to use

Type: string vector

Default: true

`delta` Delta

Type: constant  
Default: DELTA  
Lower Bound: 0.0 (exclusive)

dispersion      Dispersion parameter (A weighting factor for the likelihood)  
Type: constant  
Default: Double(1.0)

detection      Detection probability  
Type: constant  
Default: No Default

error\_value\_multiplier      Error value multiplier for likelihood  
Type: constant  
Default: Double(1.0)

length\_bins      Length Bins  
Type: constant vector  
Default: No Default

likelihood\_multiplier      Likelihood score multiplier  
Type: constant  
Default: Double(1.0)

likelihood      Type of likelihood to use  
Type: string  
Default: No Default

plus\_group      Last length bin a plus group  
Type: boolean  
Default: true

process\_errors      Process error  
Type: constant vector  
Default: true

selectivities      Selectivity labels to use  
Type: string vector  
Default: true

simulation\_likelihood      Simulation likelihood to use  
Type: string  
Default: ""

categories2      Target Categories

Type: string vector  
Default: No Default

`selectivities2`      Target Selectivities

Type: string vector  
Default: No Default

`time_step`      Time step to execute in

Type: string  
Default: No Default

`time_step_proportion`      Proportion through the time step to analyse the partition from

Type: constant  
Default: Double(0.5)

`years`      Year to execute in

Type: non-negative integer vector  
Default: No Default

## 10.2. Likelihoods

**@likelihood** *label*      Define an object type Likelihood

`label`

Type: string  
Default: No Default

`type`

Type: string  
Default: No Default

**10.2.1. @likelihood[label].type=binomial**

**10.2.2. @likelihood[label].type=binomial\_approx**

**10.2.3. @likelihood[label].type=dirichlet**

**10.2.4. @likelihood[label].type=log\_normal**

**10.2.5. @likelihood[label].type=log\_normal\_with\_q**

**10.2.6. @likelihood[label].type=multinomial**

**10.2.7. @likelihood[label].type=normal**

**10.2.8. @likelihood[label].type=pseudo**

### **10.3. Defining ageing error**

Three methods for including ageing error into estimation with observations are,

- None
- Normal
- Off-by-one

Each type of ageing error requires a set of subcommands and arguments specific to its type.

**@ageing\_error label** Define an object type Ageing\_Error

label Label

Type: string

Default: No Default

type Type

Type: string

Default: No Default

**10.3.1. @ageing\_error[label].type=data**

**10.3.2. @ageing\_error[label].type=normal**

cv CV for Misclassification matrix

Type: constant

Default: No Default

Lower Bound: 0.0 (inclusive)

k k defines the minimum age of individuals which can be misclassified, e.g., individuals under age k have no ageing error

Type: non-negative integer

Default: 0u



---

### 10.3.3. @ageing\_error[label].type=off\_by\_one

k      The minimum age of fish which can be missclassified

Type: non-negative integer

Default: 0u

Lower Bound: 0.0 (inclusive)

Upper Bound: 1.0 (inclusive)

p1      proprtion of misclassification up by a single age, i.e. Proportion of individuals at age 3 that are actually age 4

Type: constant

Default: No Default

p2      proprtion of misclassification down by a single age

Type: constant

Default: No Default

Lower Bound: 0.0 (inclusive)

Upper Bound: 1.0 (inclusive)

## 11. Report command and subcommand syntax

### 11.1. Report commands and subcommands

**@report** *label*      Define an object type Report

*file\_name*      File Name

Type: string

Default: ""

*label*      Label

Type: string

Default: No Default

*type*      Type

Type: string

Default: No Default

*write\_mode*      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

### 11.1.1. @report[label].type=ageing\_error\_matrix

ageing\_error      Ageing Error label

Type: string

Default: No Default

file\_name      File Name

Type: string

Default: ""

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

### 11.1.2. @report[label].type=category\_info

file\_name      File Name

Type: string

Default: ""

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

### 11.1.3. @report[label].type=category\_list

file\_name      File Name

Type: string

Default: ""

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

### 11.1.4. @report[label].type=correlation\_matrix

file\_name      File Name

Type: string

Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### **11.1.5. @report [label] .type=covariance matrix**

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### **11.1.6. @report [label] .type=derived quantity**

file\_name      File Name  
Type: string  
Default: ""

units      Unit of weight output expressed in  
Type: string  
Default: No Default

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### **11.1.7. @report [label] .type=estimable**

file\_name      File Name  
Type: string  
Default: ""

parameter      Parameter to print  
Type: string  
Default: No Default

time\_step      Time Step label

Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

years      Years to print the estimable for  
Type: non-negative integer vector  
Default: No Default

#### 11.1.8. @report[label].type=estimate\_summary

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### 11.1.9. @report[label].type=estimate\_value

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### 11.1.10. @report[label].type=hessian\_matrix

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode

Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### **11.1.11. @report[label].type=initialisation\_partition**

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### **11.1.12. @report[label].type=mcmc\_covariance**

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### **11.1.13. @report[label].type=mcmc\_objective**

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### **11.1.14. @report[label].type=mcmc\_sample**

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### 11.1.15. @report [label] .type=m\_p\_d

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### 11.1.16. @report [label] .type=objective\_function

file\_name      File Name  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

#### 11.1.17. @report [label] .type=observation

file\_name      File Name  
Type: string  
Default: ""

observation      Observation label  
Type: string  
Default: No Default

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

**11.1.18. @report [label] .type=output\_parameters**

file\_name      File Name

Type: string

Default: ""

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

**11.1.19. @report [label] .type=partition**

file\_name      File Name

Type: string

Default: ""

time\_step      Time Step label

Type: string

Default: ""

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

years      Years

Type: non-negative integer vector

Default: true

**11.1.20. @report [label] .type=partition\_biomass**

file\_name      File Name

Type: string

Default: ""

time\_step      Time Step label

Type: string

Default: ""

units      Units (Default Kgs)

Type: string

Default: kgs

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

years      Years  
Type: non-negative integer vector  
Default: true

#### 11.1.21. @report [label] .type=partition\_mean\_weight

file\_name      File Name  
Type: string  
Default: ""

time\_step      Time Step label  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix

years      Years  
Type: non-negative integer vector  
Default: true

#### 11.1.22. @report [label] .type=process

file\_name      File Name  
Type: string  
Default: ""

process      Process label that is reported  
Type: string  
Default: ""

write\_mode      Write mode  
Type: string  
Default: overwrite  
Allowed Values: overwrite, append, incremental\_suffix



**11.1.23. @report [label] .type=random\_number\_seed**

file\_name      File Name

Type: string

Default: ""

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

**11.1.24. @report [label] .type=selectivity**

file\_name      File Name

Type: string

Default: ""

selectivity      Selectivity name

Type: string

Default: No Default

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

**11.1.25. @report [label] .type=simulated\_observation**

file\_name      File Name

Type: string

Default: ""

observation      Observation label

Type: string

Default: No Default

write\_mode      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

### 11.1.26. **@report [label] .type=standard\_header**

`file_name`      File Name

Type: string

Default: ""

`write_mode`      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

### 11.1.27. **@report [label] .type=time\_varying**

`file_name`      File Name

Type: string

Default: ""

`write_mode`      Write mode

Type: string

Default: overwrite

Allowed Values: overwrite, append, incremental\_suffix

## 12. Other commands and subcommands

**@include** *file*      Include an external file

*file*      The name of the external file to include

Type: string

Default: No default

Value: A valid external file

Condition: The file name must be enclosed in double quotes

Example: @include "my\_file.txt"

Note: @include does not denote the end of the previous command block as is the case for all other commands

---

## 13. Examples

### 13.1. An example of a simple model

This example implements a very simple single species and area model, with recruitment, maturation, natural and fishing mortality, and an annual age increment. The population structure has ages 1 – 30<sup>+</sup> with a single category.

CASAL2 default file to search for in your current working directory is `casal2.csl2`. In this example, `casal2.csl2` specifies all the files necessary to run your CASAL2 model from your current working directory. This is done using the `!include` command as follows.

```
!include "population.csl2"
!include "reports.csl2"
!include "Observation.csl2"
!include "estimation.csl2"
```

Breaking up a CASAL2 model into sections is recommended, as it aids in readability and error checking. `population.csl2` contains the population information. The model runs from 1975-2012 and is initialised over a 120 year period prior to 1975, which applies the following processes,

1. A Beverton-Holt recruitment process, recruiting a constant number of individuals to the first age class (i.e.,  $age = 1$ ).
2. A constant mortality process representing natural mortality( $M$ ). This process is repeated in all three time steps, so that each with its own time step proportion of  $M$  applied.
3. An ageing process, where all individuals are aged by one year, and with a plus group accumulator age class at  $age = 30$ .

Following initialisation, the model runs from the years 1975 to 2012 iterating through two time-steps. The first time-step applies processes of recruitment, and  $\frac{1}{2}M_1 + F + \frac{1}{2}M_1$  processes, where  $M_1$  is the proportion of  $M$  applied in the first time step. The exploitation process (fishing) is applied in the years 1975–2012. Catches are defined in the catches table and attribute information on each fishery such as selectivity and time-step they are implemented are in the fisheries table in the `@process` block.

The second time-step applies an age increment and the remaining natural mortality.

The first 28 lines of the main section of the `population.csl2` are,

```
## Model Block
@model
start_year 1975
final_year 2012
min_age 1
max_age 30
age_plus true
initialisation_phases iphasel
time_steps step1 step2

## Category Block
@categories
format
names stock
age_lengths age_size

## Initialisation block
@initialisation_phase iphasel
type iterative
years 120

## Annual Cycle definition
@time_step step1
processes Recruitment instant_mort

@time_step step2
processes Ageing instant_mort
```

To carry out a run of the model (to verify that the model runs without any syntax errors), use the command `casal2 -r`. Note that as CASAL2 looks for a file named `casal2.txt` by default, we can override this. Hypothetically speaking if our model was all written in `Mymodel.txt` we could call it using the `-c` command like `casal2 -r -c Mymodel.txt`.

To run an estimation, and hence estimate the parameters defined in the file `estimation.csl2` (the catchability constant  $q$ , recruitment  $R_0$ , and the selectivity parameters  $a_{50}$  and  $a_{1095}$ ), use `casal2 -e`. Here, we have piped the output to `estimate.log` using the command `casal2 -e > estimate.log`, reports the user defined reports `reports.csl2` from the final iteration of the estimation, and successful convergence printed to screen,

```
Total elapsed time: 1 second
Completed
```

The main part of the output from the estimation run is summarised in the file `estimate.log`, and the final MPD parameter values can be piped out as a separate report, in this case named `paramaters.out`, using the command `casal2 -e -o paramaters.out > estimate.log`.

A profile on the  $R_0$  parameter can also be run, using `casal2 -p > profile.log`. See the examples folder for an example of the output.

KATH note below, will be useful to copy that document across. Examples on Input file specification go to the file `Input File Specification.odt` found in `CASAL2/Documentation/Software Development`

---

## 14. Post processing output using R

In the downloaded bundle is a R-package that reads CASAL2 output into R. The CASAL2 package has only one function `extract()`, which will read in the entire file. The output is written so that each @report will start with a '\*' and end with '\*end'. Users may wish to construct R or other package routines that read CASAL2 output that identify and select individual reports in the output for post-processing.



---

## 15. Troubleshooting

### 15.1. Introduction

### 15.2. Reporting errors

When reporting a bug or problem to the CASAL2 development team at [casal@niwa.co.nz](mailto:casal@niwa.co.nz), please address the following points.

### 15.3. Guidelines for reporting a problem with CASAL2

1. Detail the version of CASAL2 are you using? e.g., CASAL2 v2016-07-12Microsoft Windows executable”
2. What operating system or environment are you using? e.g., “IBM-PC Intel CPU running Microsoft Windows 10 Enterprise, Service Pack 1”.
3. Give a brief one-line description of the problem, e.g., “a segmentation fault was reported”.
4. If the problem is reproducible, please list the exact steps required to cause it, remembering to include the relevant CASAL2 configuration file, other input files, and any out generated. Specify the *exact* command line arguments that were used, e.g., “Using the command `***. -* -*` reports a segmentation fault. The input configuration files are attached.”
5. If the problem is not reproducible (only happened once, or occasionally for no apparent reason), please describe the circumstances in which it occurred and the symptoms observed (but note it is much harder to reproduce and hence fix non-reproducible bugs, but if several reports are made over time that relate to the same thing, then this may help to track down the problem), e.g., “CASAL2 crashed, but I cannot reproduce how I did it. It seemed to be related to a local network crash but I cannot be sure.”
6. If the problem causes any error messages to appear, please give the *exact* text displayed, e.g., `segmentation fault (core dumped)`.
7. Remember to attach all relevant input and output files so that the problem can be reproduced (it can helpful to compress these into a single file). Without these, it is usually not possible to determine the cause of the problem, and we are unlikely to provide any assistance. Note that it is helpful to be as specific as possible when describing the problem.





---

## 16. The Shorthand syntax section

### 16.1. Categories

CASAL2 allows many user defined categories so shorthand syntax has been added to aid in the readability of complex configuration scripts and partition structures. For example when defining categories you can use a comma for shortening lists of categories. The following syntax is how we would specify the categories the long way.

```
@categories
format sex.stage
names male.immature male.mature female.immature female.mature
```

for the exact same partition structure but specified in a shorter way users could define the categories as, (note the use of the commas),

```
@categories
format sex.stage
names male,female.immature,mature
```

CASAL2 asks for categories in processes and observations so that it can apply the right model dynamics to the right elements of the partition. For the same reason as defining categories shorthand syntax aids in readability and input management. An example of a process where categories need to be supplied as an input command is in ageing,

```
# 1. The standard way
@ageing my_ageing
categories male.immature male.mature female.immature female.mature

# 2. The 1st short-hand way
@ageing my_ageing
categories male,female.immature,mature

# 3. Wild Card (all categories)
@ageing my_ageing
categories *

# 4. The 2nd short-hand way
@ageing my_ageing
categories sex=male sex=female
```

Sometimes in observations we want to amalgamate categories together for example if we had a biomass estimate of the population that was made up of both males and females in the population you can specify this using the + special character, for example

```
@observation CPUE
type biomass
catchability Fishq
time_step one
categories male+female
selectivities FishSel
likelihood lognormal
years 1992:2001
```

```
time_step_proportion 1.0
obs 1.50 1.10 0.93 1.33 1.53 0.90 0.68 0.75 0.57 1.23
error_value 0.35
```

Shorthand syntax can be useful when applying processes to a select group of categories from the partition, for example. If we wanted to apply a spawning migration to the mature categories in the partition and the partition was defined by the categories below,

```
@categories
format area.maturity.tag
names north.immature.notag,2011 north.mature.notag,2011 south.immature.notag,2011
south.mature.notag,2011
```

If we wanted to migrate a portion of the mature population from the southern area to the northern are you could use the following syntax,

```
@process spawn_migration
type transition_category
from format=south.mature.*
to format=north.mature.*
proportions 1.0
selectivities One
```

## 16.2. Parameters

CASAL2 also allows parameters that are of type vector or map to be referenced and estimated partially. An example of a parameter that is type vector is `ycs_values` in a recruitment process. Let say a recruitment block was specified as follows,

```
@process WestRecruitment
type recruitment_beverton_holt
r0 400000
years
ycs_values 1 1 1 1 1 1 1 1
```

An alternative specification to the sequence of values you can use an astrix to shorthand repeating integers e.g.

```
ycs_values 1*8
```

```
steepness 0.9
age 1
```

Lets say we wanted to only estimate the last four values of the parameter `process[WestRecruitment].ycs_values` vector. This can be done as specified in the following **@estimate block**,

```
@estimate
parameter process[WestRecruitment].ycs_values(5:8)
type uniform
lower_bound 0.1 0.1 0.1 0.1
upper_bound 10 10 10 10
```

Note the first element of a vector is indexed by 1. This syntax can be applied to parameters that are of type map as well, for information on what type a parameter is see the syntax section. An example of a parameter that is of type map is `@time_varying[label].type=constant`. For the following `@time_varying` block,

```
@time_varying q_step1
type constant
parameter catchability[Fishq].q
years 1992 1993 1994 1995
value 0.2 0.2 0.2 0.2
```

In this example a user may want to estimate only one element of the map (say 1992), but force all other years to be the same as the one estimate. This can be done in an estimate block as follows,

```
@estimate
parameter time_varying[q_step1].value(1992)
same time_varying[q_step1].value(1993:1995)
type uniform
lower_bound 0.1 0.1 0.1 0.1
upper_bound 10 10 10 10
```

### 16.3. In line declaration

In line declarations can help shorten models by passing `@` blocks, for example

```
@observation chatCPUE
type biomass
catchability [q=6.52606e-005]
time_step one
categories male+female
selectivities chatFselMale chatFselFemale
likelihood lognormal
years 1992:2001
time_step_proportion 1.0
obs 1.50 1.10 0.93 1.33 1.53 0.90 0.68 0.75 0.57 1.23
error_value 0.35
```

```
@estimate
parameter catchability[chatTANbiomass.one].q
type uniform_log
lower_bound 1e-2
upper_bound 1
In line declaration tips
```

In the above code we are defining and estimating catchability without explicitly creating an `@catchability` block

When you do an inline declaration the new object will be created with the name of the creator's `label.index` where `index` will be the word if it's one-nine and the number if it's 10+, for example

```
@mortality halfm
selectivities [type=constant; c=1]

would create
@selectivity halfm.one
```

if there were 10 categories all with there own selectivity the 10<sup>th</sup> selectivity would be labelled;

@selectivity halfm.10

---

## 17. The Developmental section

This section is aimed for users who are interested in seeing and understanding functionality that is currently being developed and tested in CASAL2.

### 17.0.1. Single stepping CASAL2

CASAL2 has the ability to pause after each annual cycle and query the user to input updated estimable parameters for the next year. This is an active area of development for CASAL2. The aim of this is to allow CASAL2 to be used for operational management procedures or other similar studies. For example, CASAL2 could be called and controlled by **R** to update and provide management actions (for examples, catches in a fisheries model) using a harvest control rule to evaluate management strategies.

### 17.0.2. Estimate Transformations

The support of a random variable  $X$  with density  $p_X(x)$  is that subset of values for which it has non-zero density,

$$\text{supp}(X) = \{x | p_X(x) > 0\}$$

If  $f$  is a transformation function defined on the support of  $X$ , then  $Y = f(X)$  is a new random variable. This section shows the available transformations in CASAL2 and the probability density function of  $Y$ . This theory follows the STAN manual STA (2016).

Suppose  $X$  is one dimensional and  $f: \text{supp}(X) \rightarrow \mathbf{R}$  is a one-to-one, monotonic function with a differentiable inverse  $f^{-1}$ . Then the density of  $Y$  is given by

$$p_Y(y) = p_X(f^{-1}(y)) \left| \frac{\partial}{\partial y} f^{-1}(y) \right|$$

The absolute derivative of the inverse transform measures how the scale of the transformed variable changes with respect to the underlying variable.

$$Y = F_Y(X)$$

$$X = F_Y^{-1}(Y)$$

$$J =$$

#### 17.0.2.1. log

Transforming a parameter onto the log scale is a simple log transformation. The Jacobian and inverse are discussed as follows

$$F_Y = \log$$

$$F_Y^{-1} = \exp$$

$$J =$$

**17.0.2.2. Inverse**

**17.0.2.3. Log odds**

**17.0.2.4. Simplex**

---

## 18. Acknowledgements

We thank the developers of CASAL (Bull et al., 2012) for their ideas that led to the development of the CASAL2. The CASAL2 logo was designed by Ian Doonan and Erika Mackay (NIWA).

Much of the structure of CASAL2, equations, and documentation in this manual draw heavily on similar components of the fisheries population model CASAL (Bull et al., 2012) and the spatial model SPM (Dunn et al., 2015). We thank the authors of CASAL and SPM for their permission to use their work as the basis for parts of CASAL2 and allow the use of the definitions, concepts, and documentation.

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---

## 19. Quick reference

**@ageing\_error** *label*     Define an object type Ageing\_Error

label     Label

type     Type

**@ageing\_error[label].type=data**

**@ageing\_error[label].type=normal**

cv     CV for Misclassification matrix

k     k defines the minimum age of individuals which can be misclassified, e.g., individuals under age k have no ageing error

**@ageing\_error[label].type=off\_by\_one**

k     The minimum age of fish which can be missclassified

p1     proprtion of misclassification up by a single age, i.e. Proportion of individuals at age 3 that are actually age 4

p2     proprtion of misclassification down by a single age

**@age\_length** *label*     Define an object type Age\_Length

casal\_switch     A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm

cv\_first     CV for the first age class

cv\_last     CV for last age class

distribution     The assumed distribution for the growth curve

label     Label

time\_step\_proportions     the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

type     Type

**@age\_length[label].type=data**

by\_length     Specifies if the linear interpolation of CV's is a linear function of mean length at age. Default is just by age

casal\_switch     A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm

cv\_first     CV for the first age class

cv\_last     CV for last age class

distribution     The assumed distribution for the growth curve

external\_gaps

internal\_gaps

length\_weight     The label from an associated length-weight block

time\_step\_proportions     the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

**@age\_length[label].type=none**

casal\_switch     A switch to use CASAL Cumulative normal function, note CASAL2 uses the

recent BOOST function which differs from the previous CASAL algorithm

cv\_first CV for the first age class

cv\_last CV for last age class

distribution The assumed distribution for the growth curve

time\_step\_proportions the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

#### **@age\_\_length[label].type=schnute**

a Define the  $a$  parameter of the Schnute relationship

b Define the  $b$  parameter of the Schnute relationship

by\_length Specifies if the linear interpolation of CV's is a linear function of mean length at age. Default is just by age

casal\_switch A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm

cv\_first CV for the first age class

cv\_last CV for last age class

distribution The assumed distribution for the growth curve

length\_weight Define the label of the associated length-weight relationship

tau1 Define the  $\tau_1$  parameter of the Schnute relationship

tau2 Define the  $\tau_2$  parameter of the Schnute relationship

time\_step\_proportions the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

y1 Define the  $y_1$  parameter of the Schnute relationship

y2 Define the  $y_2$  parameter of the Schnute relationship

#### **@age\_\_length[label].type=von\_bertalanffy**

by\_length Specifies if the linear interpolation of CV's is a linear function of mean length at age. Default is just by age

casal\_switch A switch to use CASAL Cumulative normal function, note CASAL2 uses the recent BOOST function which differs from the previous CASAL algorithm

cv\_first CV for the first age class

cv\_last CV for last age class

distribution The assumed distribution for the growth curve

k Define the  $k$  parameter of the von Bertalanffy relationship

length\_weight Define the label of the associated length-weight relationship

linf Define the  $L_{infinity}$  parameter of the von Bertalanffy relationship

t0 Define the  $t_0$  parameter of the von Bertalanffy relationship

time\_step\_proportions the proportion increase of age through the in each time step that corresponds to a length and thus weight increase

**@catchability label** Define an object type Catchability

label Label

type

#### **@catchability[label].type=free**

q The catchability amount

**@derived\_quantity label** Define an object type Derived.Quantity

categories The list of categories to use when calculating the derived quantity

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label     Label  
time\_step\_proportion\_method  
selectivities     The list of selectivities to use when calculating the derived quantity. 1 per category  
time\_step     The time step to calculate the derived quantity after  
time\_step\_proportion  
type     Type

**@derived\_quantity[label].type=abundance**

categories     The list of categories to use when calculating the derived quantity  
time\_step\_proportion\_method  
selectivities     The list of selectivities to use when calculating the derived quantity. 1 per category  
time\_step     The time step to calculate the derived quantity after  
time\_step\_proportion

**@derived\_quantity[label].type=biomass**

categories     The list of categories to use when calculating the derived quantity  
time\_step\_proportion\_method  
selectivities     The list of selectivities to use when calculating the derived quantity. 1 per category  
time\_step     The time step to calculate the derived quantity after  
time\_step\_proportion

**@estimate label**     Define an object type Estimate

estimation\_phase     TBA  
label     Label  
lower\_bound     The lowest value the parameter is allowed to have  
mcmc     This parameter fixes parameters during an MCMC run  
parameter     The name of the variable to estimate in the model  
prior     The name of the prior to use for the parameter  
same     A list of parameters that are bound to the value of this estimate  
type     Type  
upper\_bound     The highest value the parameter is allowed to have

**@estimate[label].type=beta**

a     A  
b     B  
estimation\_phase     TBA  
lower\_bound     The lowest value the parameter is allowed to have  
mcmc     This parameter fixes parameters during an MCMC run  
mu     Mu  
parameter     The name of the variable to estimate in the model  
prior     The name of the prior to use for the parameter  
same     A list of parameters that are bound to the value of this estimate  
sigma     Sigma  
upper\_bound     The highest value the parameter is allowed to have

**@estimate[label].type=lognormal**

cv      Cv  
estimation\_phase      TBA  
lower\_bound      The lowest value the parameter is allowed to have  
mcmc      This parameter fixes parameters during an MCMC run  
mu      Mu  
parameter      The name of the variable to estimate in the model  
prior      The name of the prior to use for the parameter  
same      A list of parameters that are bound to the value of this estimate  
upper\_bound      The highest value the parameter is allowed to have

**@estimate[label].type=normal**

cv      Cv  
estimation\_phase      TBA  
lower\_bound      The lowest value the parameter is allowed to have  
mcmc      This parameter fixes parameters during an MCMC run  
mu      Mu  
parameter      The name of the variable to estimate in the model  
prior      The name of the prior to use for the parameter  
same      A list of parameters that are bound to the value of this estimate  
upper\_bound      The highest value the parameter is allowed to have

**@estimate[label].type=normal.by.stdev**

estimation\_phase      TBA  
lower\_bound      The lowest value the parameter is allowed to have  
mcmc      This parameter fixes parameters during an MCMC run  
mu      Mu  
parameter      The name of the variable to estimate in the model  
prior      The name of the prior to use for the parameter  
same      A list of parameters that are bound to the value of this estimate  
sigma      Sigma  
upper\_bound      The highest value the parameter is allowed to have

**@estimate[label].type=normal.log**

estimation\_phase      TBA  
lower\_bound      The lowest value the parameter is allowed to have  
mcmc      This parameter fixes parameters during an MCMC run  
mu      Mu  
parameter      The name of the variable to estimate in the model  
prior      The name of the prior to use for the parameter  
same      A list of parameters that are bound to the value of this estimate  
sigma      Sigma  
upper\_bound      The highest value the parameter is allowed to have

**@estimate[label].type=uniform**

estimation\_phase      TBA

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lower\_bound     The lowest value the parameter is allowed to have  
 mcmc            This parameter fixes parameters during an MCMC run  
 parameter       The name of the variable to estimate in the model  
 prior           The name of the prior to use for the parameter  
 same            A list of parameters that are bound to the value of this estimate  
 upper\_bound     The highest value the parameter is allowed to have

#### **@estimate[label].type=uniform\_log**

estimation\_phase     TBA  
 lower\_bound     The lowest value the parameter is allowed to have  
 mcmc            This parameter fixes parameters during an MCMC run  
 parameter       The name of the variable to estimate in the model  
 prior           The name of the prior to use for the parameter  
 same            A list of parameters that are bound to the value of this estimate  
 upper\_bound     The highest value the parameter is allowed to have  
**@initialisation\_phase** *label*     Define an object type Initialisation.Phase  
 label           Label  
 type            Type

#### **@initialisation\_phase[label].type=cinitial**

categories     List of categories to use

#### **@initialisation\_phase[label].type=derived**

casal\_initialisation\_switch     Reset the partition after running an extra annual cycle to take on equilibrium SSB's. Warning should only be set to true if comparing with previous CASAL models  
 exclude\_processes     The processes to exclude from all time steps  
 insert\_processes     The processes to insert in to target time steps

#### **@initialisation\_phase[label].type=iterative**

convergence\_years     The years to test for convergence  
 exclude\_processes     The processes to exclude from all time steps  
 insert\_processes     The processes to insert in to target time steps  
 lambda            Lambda  
 years            The number of iterations to execute this phase for

#### **@initialisation\_phase[label].type=state\_category\_by\_age**

categories     List of categories to use  
 max\_age     Maximum age to use for this process  
 min\_age     Minimum age to use for this process  
**@likelihood** *label*     Define an object type Likelihood  
 label  
 type

#### **@likelihood[label].type=binomial**

**@likelihood[label].type=binomial\_approx**

**@likelihood[label].type=dirichlet**

**@likelihood[label].type=log\_normal**

**@likelihood[label].type=log\_normal\_with\_q**

**@likelihood[label].type=multinomial**

**@likelihood[label].type=normal**

**@likelihood[label].type=pseudo**

**@derived\_quantity label** Define an object type `Derived_Quantity`

categories The list of categories to use when calculating the derived quantity

label Label

time\_step\_proportion\_method

selectivities The list of selectivities to use when calculating the derived quantity. 1 per

category

time\_step The time step to calculate the derived quantity after

time\_step\_proportion

type Type

**@derived\_quantity[label].type=abundance**

categories The list of categories to use when calculating the derived quantity

time\_step\_proportion\_method

selectivities The list of selectivities to use when calculating the derived quantity. 1 per

category

time\_step The time step to calculate the derived quantity after

time\_step\_proportion

**@derived\_quantity[label].type=biomass**

categories The list of categories to use when calculating the derived quantity

time\_step\_proportion\_method

selectivities The list of selectivities to use when calculating the derived quantity. 1 per

category

time\_step The time step to calculate the derived quantity after

time\_step\_proportion

**@mcmc label** Define an object type `MCMC`

active Is this the active MCMC algorithm

label Label

length The number of chain links to create

print\_default\_reports

type Type

**@mcmc[label].type=independence\_metropolis**

active Is this the active MCMC algorithm

adapt\_covariance\_matrix\_at Iterations in the chain to check and resize the MCMC stepsize

adapt\_stepsize\_at Iterations in the chain to check and resize the MCMC stepsize

correlation\_adjustment\_diff Minimum non-zero variance times the range of the bounds in

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the covariance matrix of the proposal distribution

covariance\_adjustment\_method      Method for adjusting small variances in the covariance proposal matrix

df      Degrees of freedom of the multivariate t proposal distribution

keep      Spacing between recorded values in the chain

length      The number of chain links to create

max\_correlation      Maximum absolute correlation in the covariance matrix of the proposal distribution

print\_default\_reports

proposal\_distribution      The shape of the proposal distribution (either t or normal)

start      Covariance multiplier for the starting point of the Markov chain

step\_size      Initial stepsize (as a multiplier of the approximate covariance matrix)

**@minimiser label**      Define an object type Minimiser

active      True if this minimiser is active

covariance      True if a covariance matrix should be created

label      Label

type      Type of minimiser to use

**@minimiser[label].type=adolg**

active      True if this minimiser is active

covariance      True if a covariance matrix should be created

tolerance      Tolerance of the gradient for convergence

evaluations      Maximum number of evaluations

iterations      Maximum number of iterations

step\_size      Minimum Step-size before minimisation fails

**@minimiser[label].type=betadiff**

active      True if this minimiser is active

covariance      True if a covariance matrix should be created

tolerance      Tolerance of the gradient for convergence

evaluations      Maximum number of evaluations

iterations      Maximum number of iterations

**@minimiser[label].type=cppad**

active      True if this minimiser is active

covariance      True if a covariance matrix should be created

**@minimiser[label].type=de\_solver**

active      True if this minimiser is active

covariance      True if a covariance matrix should be created

crossover\_probability      Define the minimisers crossover probability

difference\_scale      The scale to apply to new solutions when comparing candidates

max\_generations      The maximum number of iterations to run

method      The type of candidate generation method to use

population\_size      The number of candidate solutions to have in the population

tolerance      The total variance between the population and best candidate before acceptance

**@minimiser[label].type=dlib**

active      True if this minimiser is active  
covariance      True if a covariance matrix should be created

**@minimiser[label].type=numerical\_differences**

active      True if this minimiser is active  
covariance      True if a covariance matrix should be created  
tolerance      Tolerance of the gradient for convergence  
evaluations      Maximum number of evaluations  
iterations      Maximum number of iterations  
step\_size      Minimum Step-size before minimisation fails  
**@model label**      Define an object type Model  
age\_plus      Define the oldest age as a plus group  
final\_year      Define the final year of the model, excluding years in the projection period  
initialisation\_phases      Define the labels of the phases of the initialisation  
label  
length\_bins  
max\_age      Maximum age of individuals in the population  
min\_age      Minimum age of individuals in the population  
projection\_final\_year      Define the final year of the model in projection mode  
start\_year      Define the first year of the model, immediately following initialisation  
time\_steps      Define the labels of the time steps, in the order that they are applied, to form the  
annual cycle  
type      Type of model (the partition structure). Either age, length or hybrid  
**@observation label**      Define an object type Observation  
categories      Category labels to use  
error\_value\_multiplier      Error value multiplier for likelihood  
label      Label  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
simulation\_likelihood      Simulation likelihood to use  
type      Type of observation

**@observation[label].type=process\_abundance**

catchability      Abundance catchability



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categories     Category labels to use  
delta     Delta value for error values  
error\_value\_multiplier     Error value multiplier for likelihood  
error\_value     The error values to use against the observation values  
likelihood\_multiplier     Likelihood score multiplier  
likelihood     Type of likelihood to use  
obs     Observation values  
process\_error     Process error  
process     Process label  
process\_proportion     Process proportion  
selectivities     Selectivity labels to use  
simulation\_likelihood     Simulation likelihood to use  
time\_step     Time step to execute in  
years     Years to execute in

**@observation[label].type=time\_step\_abundance**

catchability     Catchability label for this observation  
categories     Category labels to use  
delta     Delta value for error values  
error\_value\_multiplier     Error value multiplier for likelihood  
error\_value     The error values to use against the observation values  
likelihood\_multiplier     Likelihood score multiplier  
likelihood     Type of likelihood to use  
obs     Observation values  
process\_error     Process error  
selectivities     Selectivity labels to use  
simulation\_likelihood     Simulation likelihood to use  
time\_step     Time step to execute in  
time\_step\_proportion     Proportion through the time step to analyse the partition from  
years     Years to execute in

**@observation[label].type=process\_biomass**

catchability     Catchability of Biomass  
categories     Category labels to use  
delta     Delta value for error values  
error\_value\_multiplier     Error value multiplier for likelihood  
error\_value     The error values to use against the observation values  
likelihood\_multiplier     Likelihood score multiplier  
likelihood     Type of likelihood to use  
obs     Observation values  
process\_error     Process error  
process     Process label  
process\_proportion     Process proportion  
selectivities     Selectivity labels to use  
simulation\_likelihood     Simulation likelihood to use  
time\_step     Time step to execute in  
years     Years to execute in

**@observation[label].type=time\_step\_biomass**

catchability    Catchability of Biomass  
categories    Category labels to use  
delta    Delta value for error values  
error\_value\_multiplier    Error value multiplier for likelihood  
error\_value    The error values to use against the observation values  
likelihood\_multiplier    Likelihood score multiplier  
likelihood    Type of likelihood to use  
obs    Observation values  
process\_error    Process error  
selectivities    Selectivity labels to use  
simulation\_likelihood    Simulation likelihood to use  
time\_step    Time step to execute in  
time\_step\_proportion    Proportion through the time step to analyse the partition from  
years    Years to execute in

**@observation[label].type=process\_proportions\_at\_age**

age\_plus    Use age plus group  
ageing\_error    Label of ageing error to use  
categories    Category labels to use  
delta    Delta  
error\_value\_multiplier    Error value multiplier for likelihood  
likelihood\_multiplier    Likelihood score multiplier  
likelihood    Type of likelihood to use  
max\_age    Maximum age  
min\_age    Minimum age  
process\_errors    Process error  
process    Process label  
process\_proportion    Process proportion  
selectivities    Selectivity labels to use  
simulation\_likelihood    Simulation likelihood to use  
time\_step    Time step to execute in  
tolerance    Tolerance  
years    Year to execute in

**@observation[label].type=time\_step\_proportions\_at\_age**

age\_plus    Use age plus group

---

ageing\_error      Label of ageing error to use  
categories      Category labels to use  
delta      Delta  
error\_value\_multiplier      Error value multiplier for likelihood  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
max\_age      Maximum age  
min\_age      Minimum age  
process\_errors      Process error  
selectivities      Selectivity labels to use  
simulation\_likelihood      Simulation likelihood to use  
time\_step      Time step to execute in  
time\_step\_proportion      Proportion through the time step to analyse the partition from  
tolerance      Tolerance  
years      Year to execute in

**@observation[label].type=proportions\_at\_age\_for\_fishery**

age\_plus      Use age plus group  
ageing\_error      Label of ageing error to use  
categories      Category labels to use  
delta      Delta  
error\_value\_multiplier      Error value multiplier for likelihood  
fishery      Label of fishery the observation is from  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
max\_age      Maximum age  
min\_age      Minimum age  
process\_errors      Process error  
process      Process label  
simulation\_likelihood      Simulation likelihood to use  
time\_step      Time steps that the fisheries are in  
tolerance      Tolerance  
years      Year to execute in

**@observation[label].type=process\_proportions\_at\_length**

categories      Category labels to use

delta      Delta  
error\_value\_multiplier      Error value multiplier for likelihood  
length\_bins      Length bins  
length\_plus\_group      Is the last bin a plus group  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
process\_errors      Process error  
process      Process label  
process\_proportion      Process proportion  
selectivities      Selectivity labels to use  
simulation\_likelihood      Simulation likelihood to use  
time\_step      Time step to execute in  
tolerance      Tolerance for rescaling proportions  
years      Year to execute in

**@observation[label].type=time\_step\_proportions\_at\_length**

categories      Category labels to use  
delta      Delta  
error\_value\_multiplier      Error value multiplier for likelihood  
length\_bins      Length bins  
length\_plus\_group      Is the last bin a plus group  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
process\_errors      Process error  
selectivities      Selectivity labels to use  
simulation\_likelihood      Simulation likelihood to use  
time\_step      Time step to execute in  
time\_step\_proportion      Proportion through the time step to analyse the partition from  
tolerance      Tolerance for rescaling proportions  
years      Year to execute in

**@observation[label].type=proportions\_at\_length\_for\_fishery**

categories      Category labels to use  
delta      Delta  
error\_value\_multiplier      Error value multiplier for likelihood  
fishery      Label of fishery the observation is from  
length\_bins      Length bins  
length\_plus\_group      Is the last bin a plus group  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
process\_errors      Process error  
process      Process label  
process\_proportion      Process proportion  
simulation\_likelihood      Simulation likelihood to use  
time\_step      Time step to execute in  
tolerance      Tolerance for rescaling proportions  
years      Year to execute in

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**@observation[label].type=process\_proportions\_by\_category**

age\_plus      Use age plus group  
categories    Category labels to use  
delta        Delta  
error\_value\_multiplier    Error value multiplier for likelihood  
likelihood\_multiplier    Likelihood score multiplier  
likelihood    Type of likelihood to use  
max\_age      Maximum age  
min\_age      Minimum age  
process\_errors    Process error  
process       Process label  
process\_proportion    Process proportion  
selectivities    Selectivity labels to use  
simulation\_likelihood    Simulation likelihood to use  
categories2    Target Categories  
selectivities2    Target Selectivities  
time\_step    Time step to execute in  
years        Year to execute in

**@observation[label].type=time\_step\_proportions\_by\_category**

age\_plus      Use age plus group  
categories    Category labels to use  
delta        Delta  
error\_value\_multiplier    Error value multiplier for likelihood  
likelihood\_multiplier    Likelihood score multiplier  
likelihood    Type of likelihood to use  
max\_age      Maximum age  
min\_age      Minimum age  
process\_errors    Process error  
selectivities    Selectivity labels to use  
simulation\_likelihood    Simulation likelihood to use  
categories2    Target Categories  
selectivities2    Target Selectivities  
time\_step    Time step to execute in  
time\_step\_proportion    Proportion through the time step to analyse the partition from  
years        Year to execute in

**@observation[label].type=proportions\_migrating**

age\_plus      Use age plus group

ageing\_error      Label of ageing error to use  
categories      Category labels to use  
delta      Delta  
error\_value\_multiplier      Error value multiplier for likelihood  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
max\_age      Maximum age  
min\_age      Minimum age  
process\_errors      Process error  
process      Process label  
process\_proportion      Process proportion  
simulation\_likelihood      Simulation likelihood to use  
time\_step      Time step to execute in  
years      Year to execute in

**@observation[label].type=tag\_recapture\_by\_age**

age\_plus      Use age plus group  
categories      Category labels to use  
delta      Delta  
detection      Detection probability  
error\_value\_multiplier      Error value multiplier for likelihood  
likelihood\_multiplier      Likelihood score multiplier  
likelihood      Type of likelihood to use  
max\_age      Maximum age  
min\_age      Minimum age  
process\_errors      Process error  
selectivities      Selectivity labels to use  
simulation\_likelihood      Simulation likelihood to use  
categories2      Target Categories  
selectivities2      Target Selectivities  
time\_step      Time step to execute in  
time\_step\_proportion      Proportion through the time step to analyse the partition from  
years      Year to execute in

**@observation[label].type=tag\_recapture\_by\_length**

categories      Category labels to use

---

delta      Delta  
 dispersion      Dispersion parameter (A weighting factor for the likelihood)  
 detection      Detection probability  
 error\_value\_multiplier      Error value multiplier for likelihood  
 length\_bins      Length Bins  
 likelihood\_multiplier      Likelihood score multiplier  
 likelihood      Type of likelihood to use  
 plus\_group      Last length bin a plus group  
 process\_errors      Process error  
 selectivities      Selectivity labels to use  
 simulation\_likelihood      Simulation likelihood to use  
 categories2      Target Categories  
 selectivities2      Target Selectivities  
 time\_step      Time step to execute in  
 time\_step\_proportion      Proportion through the time step to analyse the partition from  
 years      Year to execute in  
**@penalty** *label*      Define an object type Penalty  
 label      Label  
 type      Type

**@penalty[label].type=process**

log\_scale      Log scale  
 multiplier      Multiplier  
**@process** *label*      Define an object type Process  
 print\_report      Generate parameter report  
 label      Label  
 type      Type

**@process[label].type=ageing**

categories      Categories  
 print\_report      Generate parameter report

**@process[label].type=growth**

print\_report      Generate parameter report

**@process[label].type=maturation**

print\_report      Generate parameter report  
 from      List of categories to mature from  
 rates      The rates to mature for each year  
 selectivities      List of selectivities to use for maturation  
 to      List of categories to mature too  
 years      The years to be associated with rates

**@process[label].type=mortality\_constant\_rate**

categories      List of categories

print\_report   Generate parameter report  
m   Mortality rates  
time\_step\_ratio   Time step ratios for M  
selectivities   Selectivities

**@process[label].type=mortality\_event**

catches   Catches  
categories   Categories  
print\_report   Generate parameter report  
penalty   Penalty label  
selectivities   List of selectivities  
u\_max   U Max  
years   Years

**@process[label].type=mortality\_event\_biomass**

catches   Catches for each year  
categories   Category labels  
print\_report   Generate parameter report  
penalty   Penalty label  
selectivities   Selectivity labels  
u\_max   U Max  
units   Unit of weight that the Catches table are expressed in  
years   Years to apply mortality

**@process[label].type=mortality\_holling\_rate**

a   parameter a  
b   parameter b  
print\_report   Generate parameter report  
is\_abundance   Is vulnerable amount for prey and predator in Abundance (TRUE) or biomass (FALSE)  
penalty   Label of penalty to be applied  
predator\_categories   Predator Categories labels  
predator\_selectivities   Selectivities for predator categories  
prey\_categories   Prey Categories labels  
prey\_selectivities   Selectivities for prey categories  
u\_max   Umax  
x   This parameter controls the type of functional form, Holling function type 2 (x=2) or 3 (x=3), or generalised (Michaelis Menten)  
years   Year to execute in

**@process[label].type=mortality\_instantaneous**

categories   Categories for natural mortality  
print\_report   Generate parameter report  
m   Mortality rates  
selectivities   Selectivities for Natural Mortality  
time\_step\_ratio   Time step ratios for M  
units   Unit of weight that the Catches table are expressed in



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**@process[label].type=mortality\_prey\_suitability**

consumption\_rate    Predator consumption rate  
print\_report        Generate parameter report  
electivities        Prey Electivities  
penalty            Label of penalty to be applied  
predator\_categories    Predator Categories labels  
predator\_selectivities    Selectivities for predator categories  
prey\_categories        Prey Categories labels  
prey\_selectivities    Selectivities for prey categories  
u\_max            Umax  
years            Year that process occurs

**@process[label].type=nop**

print\_report        Generate parameter report

**@process[label].type=recruitment\_beverton\_holt**

age            Age to recruit at  
b0            B0  
units            Units of B0, if initialising model using B0  
categories        Category labels  
print\_report        Generate parameter report  
b0\_initialisation\_phase    Initialisation phase Label that b0 is from  
prior\_standardised\_ycs    Priors for year class strength on ycs values (not standardised ycs values)  
proportions        Proportions  
r0            R0  
ssb            SSB Label (derived quantity)  
ssb\_offset        Spawning biomass year offset  
standardise\_ycs\_years    Years that are included for year class standardisation  
steepness        Steepness  
ycs\_values        YCS Values

**@process[label].type=recruitment\_constant**

age            Age  
categories        Categories  
print\_report        Generate parameter report  
proportions        Proportions  
r0            R0

**@process[label].type=tag\_by\_age**

print\_report        Generate parameter report

from     Categories to transition from  
initial\_mortality  
initial\_mortality\_selectivity  
loss\_rate  
loss\_rate\_selectivities  
max\_age     Maximum age to transition  
min\_age     Minimum age to transition  
n  
penalty     Penalty label  
selectivities  
to     Categories to transition to  
u\_max     U Max  
years     Years to execute the transition in

**@process[label].type=tag\_by\_length**

print\_report     Generate parameter report  
from     Categories to transition from  
initial\_mortality  
initial\_mortality\_selectivity  
maximum\_length     The upper length when there is no plus group  
n  
penalty     Penalty label  
plus\_group     Use plus group for last length bin  
selectivities  
to     Categories to transition to  
u\_max     U Max  
years     Years to execute the transition in

**@process[label].type=tag\_loss**

categories     List of categories  
print\_report     Generate parameter report  
time\_step\_ratio     Time step ratios for Tag Loss  
selectivities     Selectivities  
tag\_loss\_rate     Tag Loss rates  
tag\_loss\_type     Type of tag loss  
year     The year the first tagging release process was executed

**@process[label].type=transition\_category**

print\_report     Generate parameter report  
from     From  
proportions     Proportions  
selectivities     Selectivity names  
to     To

**@process[label].type=transition\_category\_by\_age**

print\_report     Generate parameter report

---

from      Categories to transition from  
max\_age    Maximum age to transition  
min\_age    Minimum age to transition  
penalty    Penalty label  
to      Categories to transition to  
u\_max      U Max  
years      Years to execute the transition in  
**@profile** *label*      Define an object type Profile  
  
label      Label  
lower\_bound    The lower bounds  
parameter    The system parameter to profile  
steps      The number of steps to take between the lower and upper bound  
type  
upper\_bound    The upper bounds  
**@report** *label*      Define an object type Report  
  
file\_name    File Name  
label      Label  
type      Type  
write\_mode    Write mode

**@report [label] .type=ageing\_error\_matrix**

ageing\_error    Ageing Error label  
file\_name    File Name  
write\_mode    Write mode

**@report [label] .type=category\_info**

file\_name    File Name  
write\_mode    Write mode

**@report [label] .type=category\_list**

file\_name    File Name  
write\_mode    Write mode

**@report [label] .type=correlation\_matrix**

file\_name    File Name  
write\_mode    Write mode

**@report [label] .type=covariance\_matrix**

file\_name    File Name  
write\_mode    Write mode

**@report [label] .type=derived\_quantity**

file\_name    File Name

units      Unit of weight output expressed in  
write\_mode      Write mode

**@report[label].type=estimable**

file\_name      File Name  
parameter      Parameter to print  
time\_step      Time Step label  
write\_mode      Write mode  
years      Years to print the estimable for

**@report[label].type=estimate\_summary**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=estimate\_value**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=hessian.matrix**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=initialisation\_partition**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=mcmc\_covariance**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=mcmc\_objective**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=mcmc\_sample**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=m.p.d**

file\_name      File Name  
write\_mode      Write mode

---

**@report[label].type=objective\_function**

file\_name     File Name  
write\_mode    Write mode

**@report[label].type=observation**

file\_name     File Name  
observation    Observation label  
write\_mode    Write mode

**@report[label].type=output\_parameters**

file\_name     File Name  
write\_mode    Write mode

**@report[label].type=partition**

file\_name     File Name  
time\_step     Time Step label  
write\_mode    Write mode  
years        Years

**@report[label].type=partition\_biomass**

file\_name     File Name  
time\_step     Time Step label  
units        Units (Default Kgs  
write\_mode    Write mode  
years        Years

**@report[label].type=partition\_mean\_weight**

file\_name     File Name  
time\_step     Time Step label  
write\_mode    Write mode  
years        Years

**@report[label].type=process**

file\_name     File Name  
process       Process label that is reported  
write\_mode    Write mode

**@report[label].type=random\_number\_seed**

file\_name     File Name  
write\_mode    Write mode

**@report[label].type=selectivity**

file\_name     File Name

selectivity      Selectivity name  
write\_mode      Write mode

**@report[label].type=simulated\_observation**

file\_name      File Name  
observation      Observation label  
write\_mode      Write mode

**@report[label].type=standard\_header**

file\_name      File Name  
write\_mode      Write mode

**@report[label].type=time\_varying**

file\_name      File Name  
write\_mode      Write mode  
**@selectivity label**      Define an object type Selectivity  
label      Label  
length\_based      Is the selectivity length based  
intervals      Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
type      Type

**@selectivity[label].type=all\_values**

length\_based      Is the selectivity length based  
intervals      Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
v      V

**@selectivity[label].type=all\_values\_bounded**

h      H  
length\_based      Is the selectivity length based  
l      L  
intervals      Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
v      V

**@selectivity[label].type=constant**

c      C  
length\_based      Is the selectivity length based  
intervals      Number of quantiles to evaluate a length based selectivity over the age length  
distribution

**@selectivity[label].type=double\_exponential**

alpha      Alpha

---

length\_based      Is the selectivity length based  
 intervals      Number of quantiles to evaluate a length based selectivity over the age length  
 distribution  
 x0      X0  
 x1      X1  
 x2      X2  
 y0      Y0  
 y1      Y1  
 y2      Y2

**@selectivity[label].type=double\_normal**

alpha      Alpha  
 length\_based      Is the selectivity length based  
 mu      Mu  
 intervals      Number of quantiles to evaluate a length based selectivity over the age length  
 distribution  
 sigma\_l      Sigma L  
 sigma\_r      Sigma R

**@selectivity[label].type=increasing**

alpha      Alpha  
 h      High  
 length\_based      Is the selectivity length based  
 l      Low  
 intervals      Number of quantiles to evaluate a length based selectivity over the age length  
 distribution  
 v      V

**@selectivity[label].type=inverse\_logistic**

a50      A50  
 alpha      Alpha  
 ato95      aTo95  
 length\_based      Is the selectivity length based  
 intervals      Number of quantiles to evaluate a length based selectivity over the age length  
 distribution

**@selectivity[label].type=knife\_edge**

alpha      Alpha  
 e      Edge  
 length\_based      Is the selectivity length based  
 intervals      Number of quantiles to evaluate a length based selectivity over the age length  
 distribution

**@selectivity[label].type=logistic**

a50      A50

alpha     Alpha  
ato95     Ato95  
length.based     Is the selectivity length based  
intervals     Number of quantiles to evaluate a length based selectivity over the age length  
distribution

**@selectivity[label].type=logistic Producing**

a50     A50  
alpha     Alpha  
ato95     Ato95  
h     High  
length.based     Is the selectivity length based  
l     Low  
intervals     Number of quantiles to evaluate a length based selectivity over the age length  
distribution  
**@length.weight label**     Define an object type Length\_Weight  
label     Label  
type     Type

**@length\_\_weight[label].type=basic**

a     A  
b     B  
units     Units of measure (tonnes, kgs, grams)

**@length\_\_weight[label].type=none**

**@time.step label**     Define an object type Time\_Step

label     Label  
processes     Processes  
type



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## 22. Index

- CASAL2 source code, 2
- About CASAL2, 3
- Abundance or biomass observations, 51
- ADOL-C minimiser, 38
- Age-length relationship, 28, 82
- Ageing, 19, 22
- Ageing error, 53
- An example of a simple model, 143
- Annual cycle, 3, 13, 16, 19
- arg1, 40
- Basic length-weight relationship, 29
- Bayesian estimation, 39
- Beta prior, 43
- Betadiff minimiser, 38
- Beverton-Holt recruitment, 20
- Binomial likelihood
  - proportions-by-category, 50
- Binomial likelihood (normal approximation)
  - proportions-by-category, 51
- BOOST C++ library, 2
- Bounds, 36
- Calculation of length-at-age (in an age-based model), 29
- Calculation of mean weight, 30
- CASAL, 4
- Categories, 64, 149
- Category transition, 19
- Cinitial Initialisation, 18
- Command
  - additional\_prior, 107
  - age\_length, 82, 155
  - ageing\_error, 132, 155
  - catchability, 106, 156
  - categories, 64
  - derived\_quantity, 80, 156, 160
  - estimate, 93, 157
  - include, 142
  - Include files, 11
  - initialisation\_phase, 62, 159
  - length\_weight, 86, 178
  - likelihood, 131, 159
  - mcmc, 103, 160
  - minimiser, 100, 161
  - model, 61, 162
  - observation, 109, 162
  - penalty, 106, 169
  - process, 64, 169
  - profile, 105, 173
  - report, 133, 173
  - selectivity, 87, 176
  - time\_step, 64, 178
  - time\_varying, 77
- Command block format, 10
- Command line arguments, 7, 8
- Commands, 9
- Commands
  - Subcommands, 10
- Commenting out lines, 11
- Comments, 11
- Constant mortality, 22
- Constant Recruitment, 20
- Convergence failure, 36
- Correlation matrix, 37
- Covariance matrix, 35, 37
- CPPAD minimiser, 38
- Defining ageing error, 132
- Defining catchability constants, 106
- Defining penalties, 106
- Defining priors on parameter ratios, differences and means, 107
- Derived Initialisation, 18
- Derived quantities, 3, 27, 80
- Determining parameter names, 11
- Differential evolution minimiser, 2
- Dirichlet likelihood
  - proportions-at-age, 49
- Dlib minimiser, 38
- Estimable parameters, 7
- Estimated parameters, 4, 10
- Estimating parameters, 35
- Estimation methods, 93
- Estimation section, 4
- Event mortality, 23
- Examples, 143
- Examples
  - A simple non-spatial model, 143
  - Example 1, 143
- Exit status value, 12
- Finite differences minimiser, 1
- Fixed Initialisation, 18
- Getting help, 1
- Hessian, 35, 37
- Holling mortality, 25
- In line declaration, 151
- Include an external file, 142
- Including external files, 7
- Initialisation, 13, 16, 17, 62
  - phases, 17
- Input configuration file, 4, 7
- Input configuration file syntax, 9

- Instantaneous mortality, 24
- Interpolation of length-at-age, 29
- Iterative Initialisation, 17
- Length-weight, 86
- Likelihoods, 45, 131
- Linux, 1, 4, 7
- Local minimums, 36
- Lognormal likelihood
  - abundance, 52
  - biomass, 52
  - proportions-at-age, 49
- Lognormal prior, 43
- Maturity, in models without maturing in the partition, 30
- Maximum exploitation rate, 23, 26
- Maximum posterior density estimate (MPD), 35
- MCMC, 35, 39
- Microsoft Windows, 1, 4, 7
- Mingw, 1
- Model
  - annual cycle, 3
  - derived quantities, 3
  - initialisation, 13
  - partition, 3
  - processes, 3
  - state, 3
  - time-steps, 3
- Model overview, 3
- Model run years, 16, 18
- Model structure, 61
- Monte Carlo Markov Chain (MCMC), 35, 39, 103
- Mortality, 19, 22
- MPD (Maximum posterior density estimate), 35
- Multi-phase iteration, 17
- Multinomial likelihood
  - proportions-at-age, 48
- Necessary files, 1
- Normal likelihood
  - abundance, 53
  - biomass, 53
- Normal prior, 42
- Notifying errors, 1
- Objective function, 36
- Objective function evaluations, 36
- Observation section, 4, 5
- Observation types, 108
- Observations, 45
- Optional command line arguments, 9
- Output header information, 8
- Parameter names, 11
- Parameters, 150
- Partition, 3
- Point estimation, 36, 100
- Population processes, 19
- Population section, 4, 13
- Population structure, 13
- Posterior profiles, 38
- Print a process summary, 58
- Print derived quantities, 58
- Print observations, fits, and residuals, 58
- Print selectivities, 59
- Print simulated observations, 59
- Print the ageing error misclassification matrix, 59
- Print the covariance matrix, 58
- Print the estimated parameters, 58
- Print the estimated parameters in a vector format, 58
- Print the MCMC objective function values as they are calculated, 59
- Print the MCMC samples as they are calculated, 59
- Print the objective function, 58
- Print the partition, 57
- Print the partition at the end of an initialisation, 57
- Print the random number seed, 59
- Print the results of an MCMC, 59
- Print time varying parameters, 59
- Priors, 36
- Priors
  - Beta, 43
  - Lognormal, 43
  - Normal, 42
  - Uniform, 42
  - Uniform-log, 42
- Process error, 53
- Processes, 3, 64
- Profiles, 35, 105
- Projection year, 16
- Projection years, 18
- Proportions-at-age across aggregated categories, 47
- Proportions-at-age for a single category, 46
- Proportions-at-age for multiple categories, 46
- Proportions-at-age observations, 45
- Proportions-by-category observations, 49
- Pseudo-observations, 55
- Quasi-Newton iterations, 36
- Random number generator, 2
- Recruitment, 19, 20
- Recruitment
  - Beverton-Holt, 20
  - Constant, 20
- Redirecting standard error, 8
- Redirecting standard out, 8
- Redirecting standard output, 8
- Report commands and subcommands, 133
- Report section, 4, 5
- Reports, 57
- Reports
  - Ageing error misclassification matrix, 59
  - Covariance Matrix, 58



- Derived quantities, 58
- Estimated parameters, 58
- Hessian, 58
- Initialisation, 57
- MCMC, 59
- MCMC objective functions, 59
- MCMC samples, 59
- Objective function, 58
- Observations, 58
- Partition, 57
- Processes, 58
- Random number seed, 59
- Selectivities, 59
- Simulated observations, 59
- standard style, 57
- Tabular, 60
- time varying, 59
- Reports section, 57
- Running CASAL2, 7
- Schnute growth curve, 29
- Selectivities, 30, 87
  - All-values, 31
  - All-values-bounded, 31
  - Constant, 31
  - Double-exponential, 32
  - Double-normal, 32
  - Increasing, 31
  - Inverse-logistic, 32
  - Knife-edge, 31
  - Logistic, 32
  - Logistic-producing, 32
  - Spline, 33
- Simulating observations, 54
- Single stepping CASAL2, 19
- Single\_stepping, 19
- single\_stepping section, 19
- Size-weight relationship, 29
- Specifying the parameters to be estimated, 35
- standard error, 8
- standard output, 8
- State, 3
- Subcommand argument type, 10
- Successful convergence, 36
- System requirements, 1
- Tabular reporting, 60
- Tag Loss, 27
- Tag Release events, 27
- Tasks, 7
- Technical specifications, 1
- The differential evolution minimiser, 37
- The estimation section, 4, 35
- The numerical differences minimiser, 36
- The objective function, 35
- The observation section, 5
- The population section, 4, 13
- The report section, 5, 57
- The Shorthand syntax section, 149
- The state object and the partition, 15
- Time sequences, 16
- Time Varying Parameters, 33
  - Annual shift, 34
  - Constant, 33
  - Exogenous, 34
  - Random Walk, 33
- Time varying parameters, 77
- Time-steps, 64
- time-steps, 3
- Transition By Category, 26
- Uniform prior, 42
- Uniform-log prior, 42
- User assistance, 1
- Using CASAL2, 7
- von Bertalanffy growth curve, 28
- Weightless model, 30